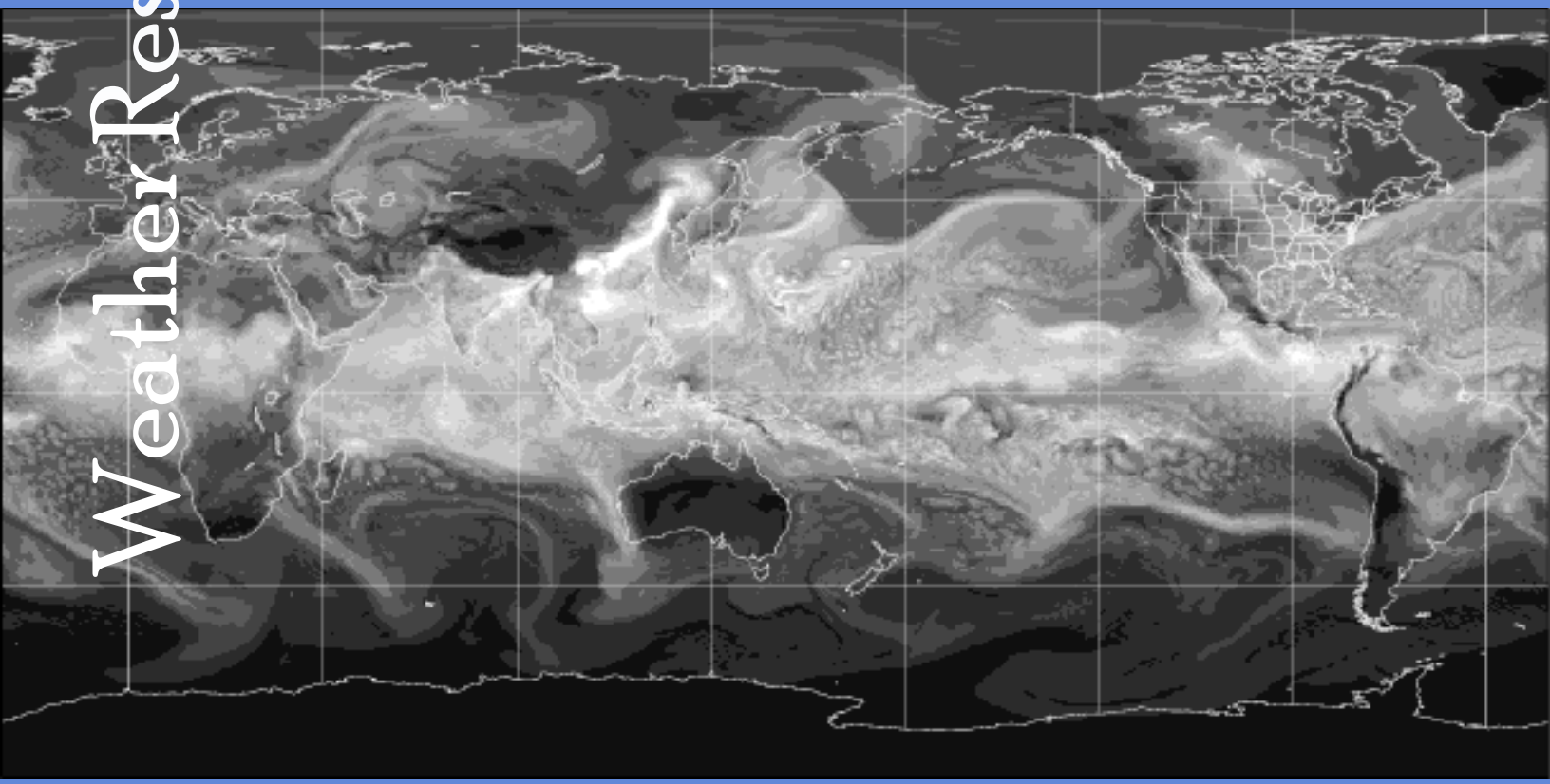
Weather Research & Forecasting

ARW

Version 3 Modeling System User's Guide

July 2010



Mesoscale & Microscale Meteorology Division • National Center for Atmospheric Research

Foreword

This User's Guide describes the Advanced Research WRF (ARW) Version 3.2 modeling system, released in April 2010. As the ARW is developed further, this document will be continuously enhanced and updated. Please send feedback to wrfhelp@ucar.edu.

This document is complementary to the ARW Tech Note (http://www.mmm.ucar.edu/wrf/users/docs/arw_v3.pdf), which describes the equations, numerics, boundary conditions, and nesting etc. in greater detail.

Highlights of updates to WRFV3.2 include:

- New physics options:
  - Milbrandt-Yau double moment microphysics
  - Building Energy Model (BEM) – a new urban physics option
  - Vegetation-height dependent thermal roughness length for MM5 and MYJ surface layer physics options
  - Sea-ice consideration in RUC and PX LSMs
  - Slope/shading effects extend to all shortwave radiation options
  - Use of semi-Lagrangian fall-term calculation in WSM and WDM schemes
  - Shallow convection option with G3 scheme
  - Garratt enthalpy flux formulation for tropical storm application
  - Single-column ocean mixed layer model extends to all surface physics options
- Nonlinear Backscatter Anisotropic (NBA) sub-grid turbulence stress for LES
- Wildland fire module
- ndown vertical nesting using constant refinement factor
- WRF-Chem updates
- WRF-DA updates:
  - Improvement on multiple outer loop minimization
  - Adjoint sensitivity tools
  - Improved efficiency for WRF adjoint code
  - PrepBufr data for 4D-Var
  - Software improvement (compile time, memory usage, etc.)
- Software framework enhancements:
  - Run-time input/output field specification and increased number of auxiliary I/O streams
  - Improved domain decomposition for MPI and OpenMP to increase the maximum number of processors/threads allowed
  - Added support for GPU acceleration of microphysics (WSM3 and WSM5) using PGI 10.3 accelerator directives
  - WRF and WPS ported to 64-bit Windows
  - Improved performance and scaling to 10^5 cores on high-end systems including Blue Gene/P and Cray XT5
  - ESMF 4 support

For the latest version of this document, please visit the ARW Users' Web site at http://www.mmm.ucar.edu/wrf/users/.

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Chapter 1: Overview

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Introduction

The Advanced Research WRF (ARW) modeling system has been in development for the past few years. The current release is Version 3, available since April 2008. The ARW is designed to be a flexible, state-of-the-art atmospheric simulation system that is portable and efficient on available parallel computing platforms. The ARW is suitable for use in a broad range of applications across scales ranging from meters to thousands of kilometers, including:

- Idealized simulations (e.g. LES, convection, baroclinic waves)
- Parameterization research
- Data assimilation research
- Forecast research
- Real-time NWP
- Hurricane research
- Regional climate research
- Coupled-model applications
- Teaching

The Mesoscale and Microscale Meteorology Division of NCAR is currently maintaining and supporting a subset of the overall WRF code (Version 3) that includes:

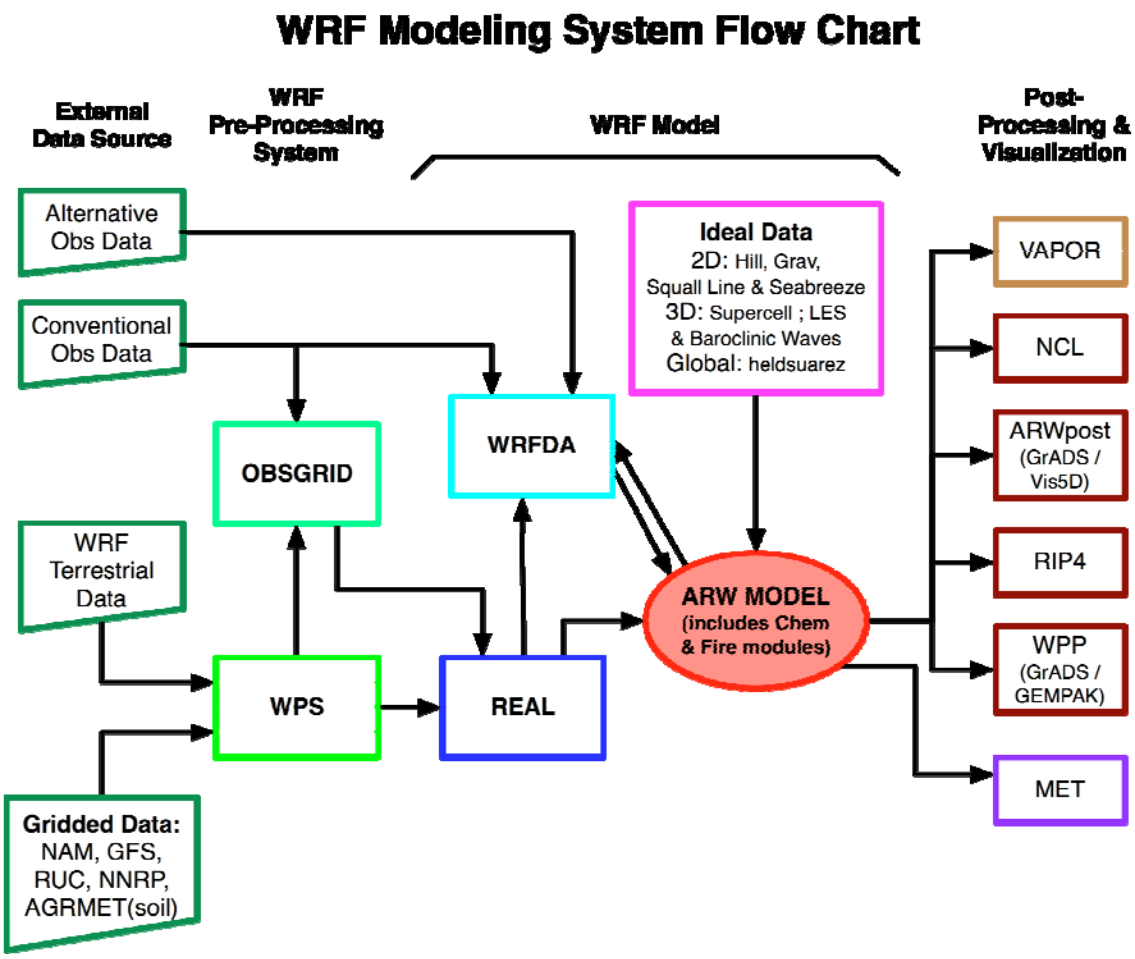
- WRF Software Framework (WSF)
- Advanced Research WRF (ARW) dynamic solver, including one-way, two-way nesting and moving nest.
- The WRF Preprocessing System (WPS)
- WRF Data Assimilation (WRF-DA) system which currently supports 3DVAR 4DVAR, and hybrid data assimilation capabilities
- Numerous physics packages contributed by WRF partners and the research community
- Several graphics programs and conversion programs for other graphics tools

And these are the subjects of this document.

The WRF modeling system software is in the public domain and is freely available for community use.

The WRF Modeling System Program Components

The following figure shows the flowchart for the WRF Modeling System Version 3.



As shown in the diagram, the WRF Modeling System consists of these major programs:

- The WRF Preprocessing System (WPS)
- WRF-Var
- ARW solver
- Post-processing & Visualization tools

WPS

This program is used primarily for real-data simulations. Its functions include 1) defining simulation domains; 2) interpolating terrestrial data (such as terrain, landuse, and soil

types) to the simulation domain; and 3) degribbing and interpolating meteorological data from another model to this simulation domain. Its main features include:

- GRIB 1/2 meteorological data from various centers around the world
- USGS 24 category and MODIS 20 category land datasets
- Map projections for 1) polar stereographic, 2) Lambert-Conformal, 3) Mercator and 4) latitude-longitude
- Nesting
- User-interfaces to input other static data as well as met data

WRFDA

This program is optional, but can be used to ingest observations into the interpolated analyses created by WPS. It can also be used to update WRF model's initial condition when WRF model is run in cycling mode. Its main features are as follows.

- It is based on incremental variational data assimilation technique, and has both 3D-Var and 4D-Var capabilities
- It also include the capability of hybrid data assimilation (Variational + Ensemble)
- Conjugate gradient method is utilized to minimized the cost function in analysis control variable space
- Analysis is performed on un-staggered Arakawa A-grid
- Analysis increments are interpolated to staggered Arakawa C-grid and it gets added to the background (first guess) to get final analysis at WRF-model grid
- Conventional observation data input may be supplied both in ASCII or “PREPBUFR” format via “obsproc” utility
- Multiple satellite observation data input may be supplied BUFR format
- Multiple radar data (reflectivity & radial velocity) input is supplied through ASCII format
- Multiple outer loop to address the nonlinearity
- Capability to compute adjoint sensitivity
- Horizontal component of the background (first guess) error is represented via recursive filter (for regional) or power spectrum (for global). The vertical component is applied through projections on climatologically generated averaged eigenvectors and its corresponding eigenvalues
- Horizontal and vertical background errors are non-separable. Each eigenvector has its own horizontal climatologically determined length scale
- Preconditioning of background part of the cost function is done via control variable transform U defined as $B= UU^T$
- It includes “gen_be” utility to generate the climatological background error covariance estimate via the NMC-method or ensemble perturbations
- A utility program to update WRF boundary condition file after WRF-DA

ARW Solver

This is the key component of the modeling system, which is composed of several initialization programs for idealized, and real-data simulations, and the numerical integration program. The key features of the WRF model include:

- Fully compressible nonhydrostatic equations with hydrostatic option
- Regional and global applications
- Complete Coriolis and curvature terms
- Two-way nesting with multiple nests and nest levels
- Concurrent one-way nesting with multiple nests and nest levels
- Offline one-way nesting with vertical nesting
- Moving nests (prescribed moves and vortex tracking)
- Mass-based terrain following coordinate
- Vertical grid-spacing can vary with height
- Map-scale factors for these projections:
    - polar stereographic (conformal)
    - Lambert-conformal
    - Mercator (conformal)
    - Latitude and longitude which can be rotated
- Arakawa C-grid staggering
- Runge-Kutta 2nd and 3rd order time integration options
- Scalar-conserving flux form for prognostic variables
- 2nd to 6th order advection options (horizontal and vertical)
- Monotonic transport and positive-definite advection option for moisture, scalar, tracer, and TKE
- Time-split small step for acoustic and gravity-wave modes:
    - small step horizontally explicit, vertically implicit
    - divergence damping option and vertical time off-centering
    - external-mode filtering option
- Upper boundary absorption and Rayleigh damping
- Lateral boundary conditions
    - idealized cases: periodic, symmetric, and open radiative
    - real cases: specified with relaxation zone
- Full physics options for land-surface, planetary boundary layer, atmospheric and surface radiation, microphysics and cumulus convection
- A single column ocean mixed layer model
- Grid analysis nudging using separate upper-air and surface data, and observation nudging
- Spectral nudging
- Digital filter initialization
- Adaptive time stepping
- Gravity wave drag
- A number of idealized examples

Graphics and Verification Tools

Several programs are supported, including RIP4 (based on NCAR Graphics), NCAR Graphics Command Language (NCL), and conversion programs for other readily available graphics packages like GrADS.

Program VAPOR, **V**isualization and **A**nalysis **P**latform for **O**cean, Atmosphere, and Solar **R**esearchers (http://www.vapor.ucar.edu/), is a 3-dimensional data visualization tool, and it is developed and supported by the VAPOR team at NCAR (vapor@ucar.edu).

Program MET, **M**odel **E**valuation **T**ools (http://www.dtcenter.org/met/users/), is developed and supported by the Developmental Testbed Center at NCAR (met_help@ucar.edu).

The details of these programs are described more in the chapters in this user's guide.

Chapter 2: Software Installation

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Introduction

The WRF modeling system software installation is fairly straightforward on the ported platforms listed below. The model-component portion of the package is mostly self-contained. The WRF model does contain the source code to a Fortran interface to ESMF and the source to FFTPACK . Contained within the WRF system is the WRFDA component, which has several external libraries that the user must install (for various observation types and linear algebra solvers). Similarly, the WPS package, separate from the WRF source code, has additional external libraries that must be built (in support of Grib2 processing). The one external package that all of the systems require is the netCDF library, which is one of the supported I/O API packages. The netCDF libraries or source code are available from the Unidata homepage at http://www.unidata.ucar.edu (select DOWNLOADS, registration required).

There are three tar files for the WRF code. The first is the WRF model (including the real and ideal pre-processors). The second is the WRFDA code. The third tar file is for WRF chemistry. In order to run the WRF chemistry code, both the WRF model and the chemistry tar file must be combined.

The WRF model has been successfully ported to a number of Unix-based machines. We do not have access to all of them and must rely on outside users and vendors to supply the required configuration information for the compiler and loader options. Below is a list of the supported combinations of hardware and software for WRF.

Vendor	Hardware	OS	Compiler
Cray	X1	UniCOS	vendor
Cray	AMD	Linux	PGI

IBM	Power Series	AIX	vendor
SGI	IA64 / Opteron	Linux	Intel
COTS*	IA32	Linux	Intel / PGI / gfortran / g95 / PathScale
COTS	IA64 / Opteron	Linux	Intel / PGI / gfortran / PathScale
Mac	Power Series	Darwin	xlf / g95 / PGI / Intel
Mac	Intel	Darwin	g95 / PGI / Intel

* Commercial Off The Shelf systems

The WRF model may be built to run on a single processor machine, a shared-memory machine (that use the OpenMP API), a distributed memory machine (with the appropriate MPI libraries), or on a distributed cluster (utilizing both OpenMP and MPI). The WRFDA and WPS packages run on the above listed systems.

Required Compilers and Scripting Languages

The majority of the WRF model, WPS, and WRFDA codes are written in Fortran (what many refer to as Fortran 90). The software layer, RSL, which sits between WRF and WRFDA, and the MPI interface is written in C. WPS makes direct calls to the MPI libraries for distributed memory message passing. There are also ancillary programs that are written in C to perform file parsing and file construction, which are required for default building of the WRF modeling code. Additionally, the WRF build mechanism uses several scripting languages: including perl, Cshell and Bourne shell. The traditional UNIX text/file processing utilities are used: make, m4, sed, and awk. See Chapter 8: WRF Software (Required Software) for a more detailed listing of the necessary pieces for the WRF build.

Required/Optional Libraries to Download

The only library that is *almost always* required is the netCDF package from Unidata (login > Downloads > NetCDF). Most of the WRF post-processing packages assume that the data from the WRF model, the WPS package, or the WRFDA program is using the netCDF libraries. One may also need to add /path-to-netcdf/netcdf/bin to your path so that one may execute netCDF utility commands, such as **ncdump**.

Note 1: If one wants to compile WRF system components on a Linux system that has access to multiple compilers, link the correct external libraries. For example, do not link the libraries built with PathScale when compiling the WRF components with gfortran. Even more, the same options when building the netCDF libraries must be used when building the WRF code (32 *vs* 64 bit, assumptions about underscores in the symbol names, etc.).

Note 2: If netCDF-4 is used, be sure that it is installed without activating the new capabilities (such as parallel I/O based on HDF5). The WRF modeling system currently only uses its classic data model supported in netCDF-4.

If you are going to be running distributed memory WRF jobs, you need a version of MPI. You can pick up a version of mpich, but you might want your system group to install the code. A working installation of MPI is required prior to a build of WRF using distributed memory. Either MPI-1 or MPI-2 are acceptable. Do you already have an MPI lying around? Try

```
which mpif90
which mpicc
which mpirun
```

If these are all defined executables in your path, you are probably OK. Make sure your paths are set up to point to the MPI **`lib`**, **`include`**, and **`bin`** directories. As with the netCDF libraries, you must build MPI consistently with the WRF source code.

Note that to output WRF model data in Grib1 format, Todd Hutchinson (WSI) has provided a complete source library that is included with the software release. However, when trying to link the WPS, the WRF model, and the WRFDA data streams together, always use the netCDF format.

Post-Processing Utilities

The more widely used (and therefore supported) WRF post-processing utilities are:

- NCL (homepage and WRF download)
  - NCAR Command Language written by NCAR's Computer Information Systems Laboratory (formerly the Scientific Computing Division)
  - NCL scripts written and maintained by WRF support
  - many template scripts are provided that are tailored for specific real-data and ideal-data cases
  - raw WRF output can be input with the NCL scripts
  - interactive or command-file driven

- GrADS (homepage and WRF download)
  - download GrADS executable, build format converter
  - programs are available to convert the WRF output into an input format suitable for GrADS
  - interpolates to regular lat/lon grid
  - simple to generate publication quality
- RIP (homepage and WRF download)
  - RIP4 written and maintained by Mark Stoelinga, UW
  - interpolation to various surfaces, trajectories, hundreds of diagnostic calculations
  - Fortran source provided
  - based on the NCAR Graphics package
  - pre-processor converts WRF, WPS, and WRFDA data to RIP input format
  - table driven

UNIX Environment Settings

There are only a few environmental settings that are WRF system related. Most of these are not required, but when things start acting badly, test some out. In Cshell syntax:

- **`setenv WRF_EM_CORE 1`**
  - explicitly defines which model core to build
- **`setenv WRF_NMM_CORE 0`**
  - explicitly defines which model core NOT to build
- **`setenv WRF_DA_CORE 0`**
  - explicitly defines no data assimilation
- **`setenv NETCDF /usr/local/netcdf`** (or where ever you have it stuck)
  - all of the WRF components want both the lib and the include directories

- **`setenv OMP_NUM_THREADS`** ***n*** (where ***n*** is the number of procs to use)
  - if you have OpenMP on your system, this is how to specify the number of threads
- **`setenv MP_STACK_SIZE 64000000`**
  - OpenMP blows through the stack size, set it large.
  - However, if the model still crashes, it may be a problem of over specifying stack size. Set stack size sufficiently large, but not unlimited.
  - On some system, the equivalent parameter could be KMP_STACKSIZE, or OMP_STACKSIZE.
- **`unlimit`**
  - especially if you are on a small system

Building the WRF Code

The WRF code has a fairly complicated build mechanism. It tries to determine the architecture that you are on, and then presents you with options to allow you to select the preferred build method. For example, if you are on a Linux machine, it determines whether this is a 32 or 64 bit machine, and then prompts you for the desired usage of processors (such as serial, shared memory, or distributed memory). You select from among the available compiling options in the build mechanism. For example, do not choose a PGI build if you do not have PGI compilers installed on your system.

- Get the WRF zipped tar file from WRFV3 from
  - **`http://www.mmm.ucar.edu/wrf/users/download/get_source.html`**
  - always get the latest version if you are not trying to continue a long project
- unzip and untar the file
  - **`gzip -cd WRFV3.TAR.gz | tar -xf –`**
  - alternatively **`tar –xzf WRFV3.TAR.gz`** on some systems
- `cd WRFV3`
- **`./configure`**
  - **serial** means single processor
  - **smpar** means Symmetric Multi-Processing/Shared Memory Parallel (OpenMP) – this does not reliably work on most non-IBM machines
  - **dmpar** means Distributed Memory Parallel (MPI)
  - **dm+sm** means Distributed Memory with Shared Memory (for example, MPI across nodes with OpenMP within a node) – usually better performance is through **dmpar** only
  - the second option is for nesting: 0 = no nesting, 1 = standard static nesting, 2 = nesting with a prescribed set of moves, 3 = nesting that allows a domain to follow a vortex (typhoon tracking)
- **`./compile em_real`** (or any of the directory names in **`./WRFV3/test`** directory)
- **`ls -ls main/*.exe`**
  - if you built a real-data case, you should see **ndown.exe**, **real.exe**, and **wrf.exe**
  - if you built an ideal-data case, you should see **ideal.exe** and **wrf.exe**

Users wishing to run the WRF chemistry code must first download the WRF model tar file, and untar it. Then the chemistry code is untar'ed in the WRFV3 directory (this is the **`chem`** directory structure). Once the source code from the tar files is combined, then users may proceed with the WRF chemistry build.

Building the WPS Code

Building WPS requires that WRFV3 is already built.

- Get the WPS zipped tar file WPSV3.TAR.gz from
  - **`http://www.mmm.ucar.edu/wrf/users/download/get_source.html`**
- Also download the geographical dataset from the same page, there are two choices based on the dataset size
- unzip and untar the source code file
  - **`gzip -cd WPSV3.TAR.gz | tar -xf -`**
- **`cd WPS`**
- **`./configure`**
  - choose one of the options
  - usually, option "1" and option “2” are for serial builds, that is the best for an initial test, most large domains work with a single processor for WPS
  - WPS requires that you build for the appropriate Grib decoding, select an option that is suitable for the data you will use with the ungrib program (the Grib2 option will work for either Grib1 or Grib2 data)
  - If you select a Grib2 option, you must have those libraries prepared and built in advance (see the chapter on WPS for the location of these compression libraries)
- **`./compile`**
- **`ls -ls *.exe`**
  - you should see **`geogrid.exe`**, **`ungrib.exe`**, and **`metgrid.exe`** (if you are missing both **`geogrid.exe`** and **`metgrid.exe`**, you probably need to fix where the path to WRF is pointing in the **`configure.wps`** file; if you are missing **`ungrib.exe`**, try a Grib1-only build to further isolate the problem)
- **`ls -ls util/*.exe`**
  - you should see a number of utility executables: **`avg_tsfc.exe`**, **`calc_ecmwf_p.exe`**, **`g1print.exe`**, **`g2print.exe`**, **`height_ukmo.exe`**, **`mod_levs.exe`**, **`plotfmt.exe`**, **`plotgrids.exe`**, and **`rd_intermediate.exe`** (files requiring NCAR Graphics are **`plotfmt.exe`** and **`plotgrids.exe`**)
- if **`geogrid.exe`** and **`metgrid.exe`** executables are missing, probably the path to the WRFV3 directory structure is incorrect (found inside the **`configure.wps`** file)
- if the **`ungrib.exe`** is missing, probably the Grib2 libraries are not linked or built correctly
- if the **`plotfmt.exe`** or the **`plotgrids.exe`** programs are missing, probably the NCAR Graphics path is set incorrectly

Building the WRFDA Code

WRFDA uses the same build mechanism as WRF, and as a consequence, this mechanism must be instructed to configure and build the code for WRFDA rather than WRF. Additionally, the paths to libraries needed by WRFDA code must be set, as described in the steps below.

- Get the WRFDA zipped tar file, WRFDAV3.TAR.gz, from **`http://www.mmm.ucar.edu/wrf/users/download/get_source.html`**
- Unzip and untar the WRFDA code
  - **`gzip -cd WRFDAV3.TAR.gz | tar -xf –`**
  - This will create a directory, **`WRFDA`**
- **`cd WRFDA`**
  - In addition to NETCDF, set up environment variables pointing to additional libraries required by WRFDA.
  - Please note: only NETCDF library is mandatory to compile basic WRFDA system, all other libraries are optional.
  - Only if you intend to use PREPBUFR observation data from NCEP, environment variable BUFR has to be set with

    `setenv BUFR 1`

  - Only if you intend to use satellite radiance data, either CRTM or RTTOV (V8.7) has to be installed. The latest available CRTM version 2.0.2 is included in this release version and it will be compiled automatically when appropriate environmental variable is set. Users do not need to download the CRTM and install it. However, RTTOV still need to be downloaded **`(http://www.metoffice.gov.uk/science/creating/working_together/nwpsaf_public.html)`** and installed using the same compiler as will be used to build WRFDA, since the library produced by one compiler may not be compatible with code compiled with another.

- Assuming, CRTM will be used to assimilate radiance data, the necessary environment variable should be set with
  - **`setenv CRTM 1 (CRTM will be compiled and installed under var/external/crtm directory automatically)`**

  OR/AND for example, that RTTOV have been installed in subdirectories of /usr/local, the necessary environment variable should be set with

  - **`setenv RTTOV /usr/local/rttov87  (make sure librttov.a is in $RTTOV directory)`**

- **`./configure wrfda`**
  - **serial** means single processor
  - **smpar** means Symmetric Multi-Processing/Shared Memory Parallel (OpenMP)
  - **dmpar** means Distributed Memory Parallel (MPI)
  - **dm+sm** means Distributed Memory with Shared Memory (for example, MPI across nodes with OpenMP within a node)
- **`./compile all_wrfvar`**
- **`ls -ls var/build/*.exe`**
  - If the compilation was successful, **`da_wrfvar.exe`**, **`da_update_bc.exe`**, and other executables should be found in the var/build directory and their links are in var/da directory; **`obsproc.exe`** should be found in the var/obsproc/src directory

Chapter 3: WRF Preprocessing System (WPS)

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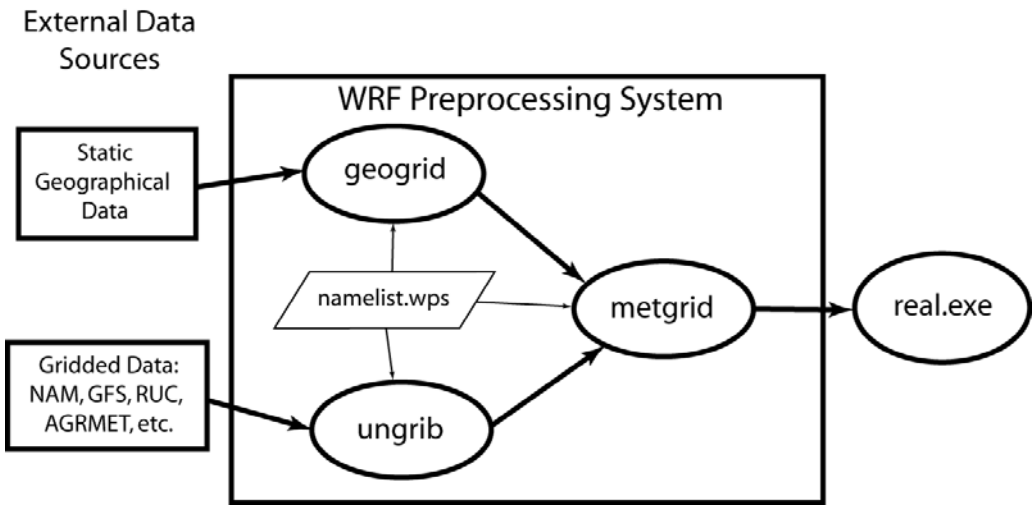
Introduction

The WRF Preprocessing System (WPS) is a set of three programs whose collective role is to prepare input to the *real* program for real-data simulations. Each of the programs performs one stage of the preparation: *geogrid* defines model domains and interpolates static geographical data to the grids; *ungrib* extracts meteorological fields from GRIB-formatted files; and *metgrid* horizontally interpolates the meteorological fields extracted by ungrib to the model grids defined by geogrid. The work of vertically interpolating meteorological fields to WRF eta levels is performed within the *real* program.



The data flow between the programs of the WPS is shown in the figure above. Each of the WPS programs reads parameters from a common namelist file, as shown in the figure. This namelist file has separate namelist records for each of the programs and a shared namelist record, which defines parameters that are used by more than one WPS program. Not shown in the figure are additional table files that are used by individual programs. These tables provide additional control over the programs' operation, though they generally do not need to be changed by the user. The GEOGRID.TBL, METGRID.TBL, and Vtable files are explained later in this document, though for now, the user need not be concerned with them.

The build mechanism for the WPS, which is very similar to the build mechanism used by the WRF model, provides options for compiling the WPS on a variety of platforms. When MPICH libraries and suitable compilers are available, the metgrid and geogrid programs may be compiled for distributed memory execution, which allows large model domains to be processed in less time. The work performed by the ungrib program is not amenable to parallelization, so ungrib may only be run on a single processor.

Function of Each WPS Program

The WPS consists of three independent programs: *geogrid*, *ungrib*, and *metgrid*. Also included in the WPS are several utility programs, which are described in the section on utility programs. A brief description of each of the three main programs is given below, with further details presented in subsequent sections.

Program geogrid

The purpose of geogrid is to define the simulation domains, and interpolate various terrestrial data sets to the model grids. The simulation domains are defined using

information specified by the user in the “geogrid” namelist record of the WPS namelist file, namelist.wps. In addition to computing the latitude, longitude, and map scale factors at every grid point, geogrid will interpolate soil categories, land use category, terrain height, annual mean deep soil temperature, monthly vegetation fraction, monthly albedo, maximum snow albedo, and slope category to the model grids by default. Global data sets for each of these fields are provided through the WRF download page, and, because these data are time-invariant, they only need to be downloaded once. Several of the data sets are available in only one resolution, but others are made available in resolutions of 30", 2', 5', and 10'; here, " denotes arc seconds and ' denotes arc minutes. The user need not download all available resolutions for a data set, although the interpolated fields will generally be more representative if a resolution of data near to that of the simulation domain is used. However, users who expect to work with domains having grid spacings that cover a large range may wish to eventually download all available resolutions of the static terrestrial data.

Besides interpolating the default terrestrial fields, the geogrid program is general enough to be able to interpolate most continuous and categorical fields to the simulation domains. New or additional data sets may be interpolated to the simulation domain through the use of the table file, GEOGRID.TBL. The GEOGRID.TBL file defines each of the fields that will be produced by geogrid; it describes the interpolation methods to be used for a field, as well as the location on the file system where the data set for that field is located.

Output from geogrid is written in the WRF I/O API format, and thus, by selecting the NetCDF I/O format, geogrid can be made to write its output in NetCDF for easy visualization using external software packages, including ncview, NCL, and the new release of RIP4.

Program ungrib

The ungrib program reads GRIB files, "degribs" the data, and writes the data in a simple format, called the intermediate format (see the section on writing data to the intermediate format for details of the format). The GRIB files contain time-varying meteorological fields and are typically from another regional or global model, such as NCEP's NAM or GFS models. The ungrib program can read GRIB Edition 1 and, if compiled with a "GRIB2" option, GRIB Edition 2 files.

GRIB files typically contain more fields than are needed to initialize WRF. Both versions of the GRIB format use various codes to identify the variables and levels in the GRIB file. Ungrib uses tables of these codes – called Vtables, for "variable tables" – to define which fields to extract from the GRIB file and write to the intermediate format. Details about the codes can be found in the WMO GRIB documentation and in documentation from the originating center. Vtables for common GRIB model output files are provided with the ungrib software.

Vtables are provided for NAM 104 and 212 grids, the NAM AWIP format, GFS, the NCEP/NCAR Reanalysis archived at NCAR, RUC (pressure level data and hybrid

coordinate data), AFWA's AGRMET land surface model output, ECMWF, and other data sets. Users can create their own Vtable for other model output using any of the Vtables as a template; further details on the meaning of fields in a Vtable are provided in the section on creating and editing Vtables.

Ungrib can write intermediate data files in any one of three user-selectable formats: WPS – a new format containing additional information useful for the downstream programs; SI – the previous intermediate format of the WRF system; and MM5 format, which is included here so that ungrib can be used to provide GRIB2 input to the MM5 modeling system. Any of these formats may be used by WPS to initialize WRF, although the WPS format is recommended.

Program metgrid

The metgrid program horizontally interpolates the intermediate-format meteorological data that are extracted by the ungrib program onto the simulation domains defined by the geogrid program. The interpolated metgrid output can then be ingested by the WRF real program. The range of dates that will be interpolated by metgrid are defined in the "share" namelist record of the WPS namelist file, and date ranges must be specified individually in the namelist for each simulation domain. Since the work of the metgrid program, like that of the ungrib program, is time-dependent, metgrid is run every time a new simulation is initialized.

Control over how each meteorological field is interpolated is provided by the METGRID.TBL file. The METGRID.TBL file provides one section for each field, and within a section, it is possible to specify options such as the interpolation methods to be used for the field, the field that acts as the mask for masked interpolations, and the grid staggering (e.g., U, V in ARW; H, V in NMM) to which a field is interpolated.

Output from metgrid is written in the WRF I/O API format, and thus, by selecting the NetCDF I/O format, metgrid can be made to write its output in NetCDF for easy visualization using external software packages, including the new version of RIP4.

Installing the WPS

The WRF Preprocessing System uses a build mechanism similar to that used by the WRF model. External libraries for geogrid and metgrid are limited to those required by the WRF model, since the WPS uses the WRF model's implementations of the WRF I/O API; consequently, *WRF must be compiled prior to installation of the WPS* so that the I/O API libraries in the WRF external directory will be available to WPS programs. Additionally, the ungrib program requires three compression libraries for GRIB Edition 2 support; however, if support for GRIB2 data is not needed, ungrib can be compiled without these compression libraries.

Required Libraries

The only library that is required to build the WRF model is NetCDF. The user can find the source code, precompiled binaries, and documentation at the UNIDATA home page (http://www.unidata.ucar.edu/software/netcdf/). Most users will select the NetCDF I/O option for WPS due to the easy access to utility programs that support the NetCDF data format, and before configuring the WPS, users should ensure that the environment variable NETCDF is set to the path of the NetCDF installation.

Where WRF adds a software layer between the model and the communications package, the WPS programs geogrid and metgrid make MPI calls directly. Most multi-processor machines come preconfigured with a version of MPI, so it is unlikely that users will need to install this package by themselves.

Three libraries are required by the ungrib program for GRIB Edition 2 compression support. Users are encouraged to engage their system administrators for the installation of these packages so that traditional library paths and include paths are maintained. Paths to user-installed compression libraries are handled in the `configure.wps` file by the `COMPRESSION_LIBS` and `COMPRESSION_INC` variables.

1) JasPer (an implementation of the JPEG2000 standard for "lossy" compression)
http://www.ece.uvic.ca/~mdadams/jasper/
Go down to “JasPer software”, one of the "click here" parts is the source.

```
> ./configure
> make
> make install
```

Note: The GRIB2 libraries expect to find include files in "jasper/jasper.h", so it may be necessary to manually create a "jasper" subdirectory in the "include" directory created by the JasPer installation, and manually link header files there.

2) PNG (compression library for "lossless" compression)
http://www.libpng.org/pub/png/libpng.html
Scroll down to "Source code" and choose a mirror site.

```
> ./configure
> make check
> make install
```

3) zlib (a compression library used by the PNG library)
http://www.zlib.net/
Go to "The current release is publicly available here" section and download.

```
> ./configure
> make
> make install
```

To get around portability issues, the NCEP GRIB libraries, w3 and g2, have been included in the WPS distribution. The original versions of these libraries are available for download from NCEP at http://www.nco.ncep.noaa.gov/pmb/codes/GRIB2/. The specific tar files to download are g2lib and w3lib. Because the ungrib program requires modules from these files, they are not suitable for usage with a traditional library option during the link stage of the build.

Required Compilers and Scripting Languages

The WPS requires the same Fortran and C compilers as were used to build the WRF model, since the WPS executables link to WRF's I/O API libraries. After executing the `./configure` command in the WPS directory, a list of supported compilers on the current system architecture are presented.

WPS Installation Steps

- Download the `WPSV3.TAR.gz` file and unpack it at the same directory level as WRFV3, as shown below.

```
> ls
-rw-r--r--  1  563863 WPS.TAR.gz
drwxr-xr-x 18    4096 WRFV3

> gzip -d WPSV3.TAR.gz

> tar xf WPSV3.TAR

> ls
drwxr-xr-x  7     4096 WPS
-rw-r--r--  1  3491840 WPSV3.TAR
drwxr-xr-x 18     4096 WRFV3
```

- At this point, a listing of the current working directory should at least include the directories WRFV3 and WPS. First, compile WRF (see the instructions for installing WRF). Then, after the WRF executables are generated, change to the WPS directory and issue the configure command followed by the compile command as below.

```
> cd WPS

> ./configure
```

  - Choose one of the configure options

```
> ./compile >& compile.output
```

- After issuing the compile command, a listing of the current working directory should reveal symbolic links to executables for each of the three WPS programs: geogrid.exe, ungrib.exe, and metgrid.exe. If any of these links do not exist, check the compilation output in compile.output to see what went wrong.

```
> ls
drwxr-xr-x 2   4096 arch
-rwxr-xr-x 1   1672 clean
-rwxr-xr-x 1   3510 compile
-rw-r--r-- 1  85973 compile.output
-rwxr-xr-x 1   4257 configure
-rw-r--r-- 1   2486 configure.wps
drwxr-xr-x 4   4096 geogrid
lrwxrwxrwx 1     23 geogrid.exe -> geogrid/src/geogrid.exe
-rwxr-xr-x 1   1328 link_grib.csh
drwxr-xr-x 3   4096 metgrid
lrwxrwxrwx 1     23 metgrid.exe -> metgrid/src/metgrid.exe
-rw-r--r-- 1   1101 namelist.wps
-rw-r--r-- 1   1987 namelist.wps.all_options
-rw-r--r-- 1   1075 namelist.wps.global
-rw-r--r-- 1    652 namelist.wps.nmm
-rw-r--r-- 1   4786 README
drwxr-xr-x 4   4096 ungrib
lrwxrwxrwx 1     21 ungrib.exe -> ungrib/src/ungrib.exe
drwxr-xr-x 3   4096 util
```

Running the WPS

There are essentially three main steps to running the WRF Preprocessing System:

1. Define a model coarse domain and any nested domains with *geogrid*.
2. Extract meteorological fields from GRIB data sets for the simulation period with *ungrib*.
3. Horizontally interpolate meteorological fields to the model domains with *metgrid*.

When multiple simulations are to be run for the same model domains, it is only necessary to perform the first step once; thereafter, only time-varying data need to be processed for each simulation using steps two and three. Similarly, if several model domains are being run for the same time period using the same meteorological data source, it is not necessary to run ungrib separately for each simulation. Below, the details of each of the three steps are explained.

Step 1: Define model domains with geogrid

In the root of the WPS directory structure, symbolic links to the programs geogrid.exe, ungrib.exe, and metgrid.exe should exist if the WPS software was successfully installed. In addition to these three links, a namelist.wps file should exist. Thus, a listing in the WPS root directory should look something like:

```
> ls
drwxr-xr-x 2   4096 arch
-rwxr-xr-x 1   1672 clean
-rwxr-xr-x 1   3510 compile
-rw-r--r-- 1  85973 compile.output
-rwxr-xr-x 1   4257 configure
-rw-r--r-- 1   2486 configure.wps
```

```
drwxr-xr-x 4   4096 geogrid
lrwxrwxrwx 1     23 geogrid.exe -> geogrid/src/geogrid.exe
-rwxr-xr-x 1   1328 link_grib.csh
drwxr-xr-x 3   4096 metgrid
lrwxrwxrwx 1     23 metgrid.exe -> metgrid/src/metgrid.exe
-rw-r--r-- 1   1101 namelist.wps
-rw-r--r-- 1   1987 namelist.wps.all_options
-rw-r--r-- 1   1075 namelist.wps.global
-rw-r--r-- 1    652 namelist.wps.nmm
-rw-r--r-- 1   4786 README
drwxr-xr-x 4   4096 ungrib
lrwxrwxrwx 1     21 ungrib.exe -> ungrib/src/ungrib.exe
drwxr-xr-x 3   4096 util
```

The model coarse domain and any nested domains are defined in the “geogrid” namelist record of the namelist.wps file, and, additionally, parameters in the “share” namelist record need to be set. An example of these two namelist records is given below, and the user is referred to the description of namelist variables for more information on the purpose and possible values of each variable.

```
&share
 wrf_core = 'ARW',
 max_dom = 2,
 start_date = '2008-03-24_12:00:00','2008-03-24_12:00:00',
 end_date   = '2008-03-24_18:00:00','2008-03-24_12:00:00',
 interval_seconds = 21600,
 io_form_geogrid = 2
/

&geogrid
 parent_id         =   1,   1,
 parent_grid_ratio =   1,   3,
 i_parent_start    =   1,  31,
 j_parent_start    =   1,  17,
 s_we              =   1,   1,
 e_we              =  74, 112,
 s_sn              =   1,   1,
 e_sn              =  61,  97,
 geog_data_res     = '10m','2m',
 dx = 30000,
 dy = 30000,
 map_proj = 'lambert',
 ref_lat   = 34.83,
 ref_lon   = -81.03,
 truelat1  =  30.0,
 truelat2  =  60.0,
 stand_lon = -98.,
 geog_data_path = '/mmm/users/wrfhelp/WPS_GEOG/'
/
```

To summarize a set of typical changes to the “share” namelist record relevant to geogrid, the WRF dynamical core must first be selected with `wrf_core`. If WPS is being run for an ARW simulation, `wrf_core` should be set to `'ARW'`, and if running for an NMM simulation, it should be set to `'NMM'`. After selecting the dynamical core, the total number of domains (in the case of ARW) or nesting levels (in the case of NMM) must be chosen with `max_dom`. Since geogrid produces only time-independent data, the `start_date`, `end_date`, and `interval_seconds` variables are ignored by geogrid. Optionally, a location (if not the default, which is the current working directory) where domain files

should be written to may be indicated with the `opt_output_from_geogrid_path` variable, and the format of these domain files may be changed with `io_form_geogrid`.

In the "geogrid" namelist record, the projection of the simulation domain is defined, as are the size and location of all model grids. The map projection to be used for the model domains is specified with the `map_proj` variable. Each of the four possible map projections in the ARW are shown graphically in the full-page figure below, and the namelist variables used to set the parameters of the projection are summarized in the following table.

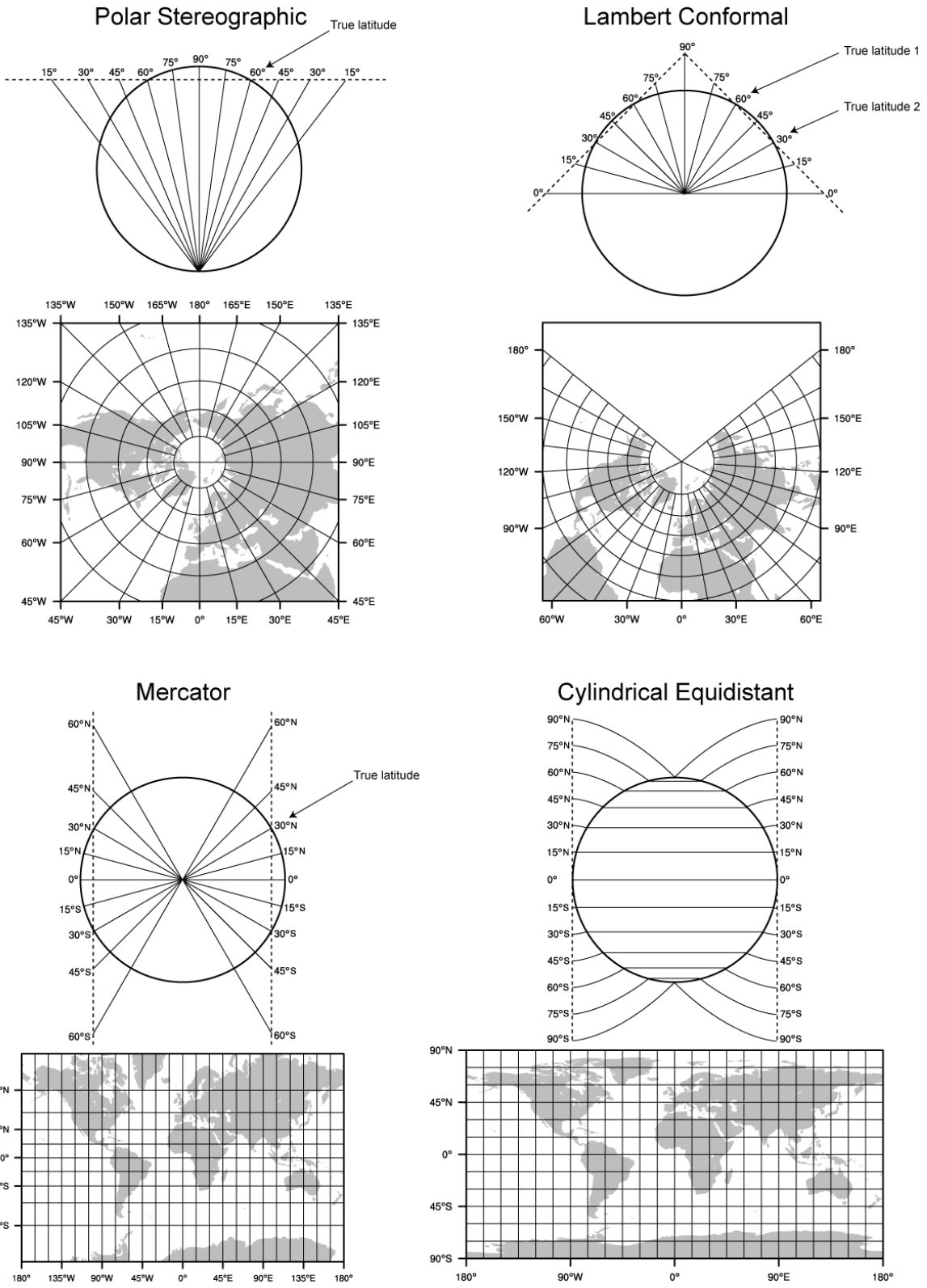
Map projection / value of `map_proj`	Projection parameters

`Lambert Conformal / 'lambert'`	`truelat1`
	`truelat2` (optional)
	`stand_lon`

Mercator / `'mercator'`	`truelat1`
Polar stereographic / `'polar'`	`truelat1` `stand_lon`

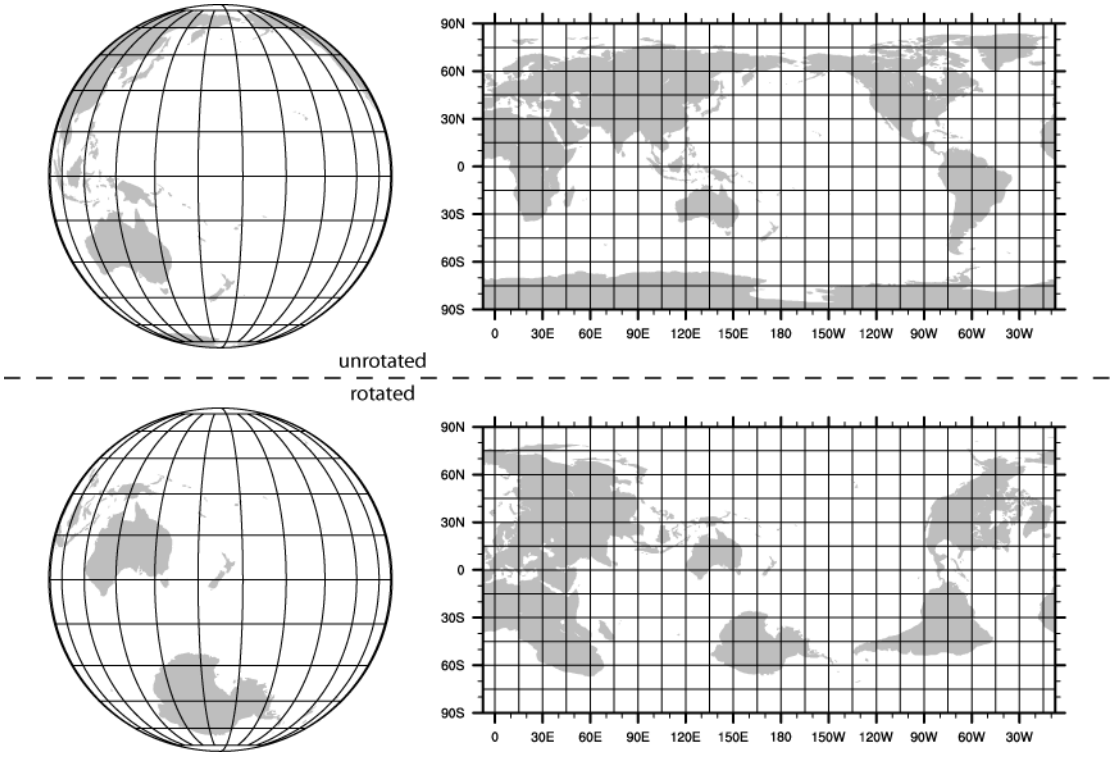
Regular latitude-longitude, or cylindrical equidistant / `'lat-lon'`	`pole_lat`
	`pole_lon`
	`stand_lon`

In the illustrations of the Lambert conformal, polar stereographic, and Mercator projections, it may be seen that the so-called true latitude (or true latitudes, in the case of the Lambert conformal), is the latitude at which the surface of projection intersects or is tangent to the surface of the earth. At this latitude, there is no distortion in the distances in the map projection, while at other latitudes, the distance on the surface of the earth is related to the distance on the surface of projection by a *map scale factor*. Ideally, the map projection and its accompanying parameters should be chosen to minimize the maximum distortion within the area covered by the model grids, since a high amount of distortion, evidenced by map scale factors significantly different from unity, can restrict the model time step more than necessary. As a general guideline, the polar stereographic projection is best suited for high-latitude WRF domains, the Lambert conformal projection is well-suited for mid-latitude domains, and the Mercator projection is good for low-latitude domains or domains with predominantly west-east extent. The cylindrical equidistant projection is required for global ARW simulations, although in its rotated aspect (i.e., when `pole_lat`, `pole_lon`, and `stand_lon` are changed from their default values) it can also be well-suited for regional domains anywhere on the earth's surface.


Polar Stereographic
True latitude
15° 30° 45° 60° 75° 90° 75° 60° 45° 30° 15°
135°W 150°W 165°W 180° 165°E 150°E 135°E
135°W 120°W 105°W 90°W 75°W 60°W 45°W
135°E 120°E 105°E 90°E 75°E 60°E 45°E
45°W 30°W 15°W 0° 15°E 30°E 45°E
Lambert Conformal
True latitude 1
True latitude 2
90° 75° 60° 45° 30° 15° 0°
180° 150°W 120°W 90°W
180° 150°E 120°E 90°E
60°W 30°W 0° 30°E 60°E
Mercator
True latitude
60°N 45°N 30°N 15°N 0° 15°S 30°S 45°S 60°S
60°N 30°N 0° 30°S 60°S
180° 135°W 90°W 45°W 0° 45°E 90°E 135°E 180°
Cylindrical Equidistant
90°N 75°N 60°N 45°N 30°N 15°N 0° 15°S 30°S 45°S 60°S 75°S 90°S
90°N 45°N 0° 45°S 90°S
180° 90°W 0° 90°E 180°

When configuring a rotated latitude-longitude grid, the namelist parameters `pole_lat`, `pole_lon`, and `stand_lon` are changed from their default values. The parameters `pole_lat` and `pole_lon` specify the latitude and longitude of the geographic north pole within the model's *computational grid*, and `stand_lon` gives the rotation about the earth's axis. In the context of the ARW, the computational grid refers to the regular latitude-longitude grid on which model computation is done, and on whose latitude circles Fourier filters are applied at high latitudes; users interested in the details of this filtering are referred to the WRF Version 3 Technical Note, and here, it suffices to note that the computational latitude-longitude grid is always represented with computational latitude lines running parallel to the x-axis of the model grid and computational longitude lines running parallel to the y-axis of the grid.

If the earth's geographic latitude-longitude grid coincides with the computational grid, a global ARW domain shows the earth's surface as it is normally visualized on a regular latitude-longitude grid. If instead the geographic grid does not coincide with the model computational grid, geographical meridians and parallels appear as complex curves. The difference is most easily illustrated by way of example. In top half of the figure below, the earth is shown with the geographical latitude-longitude grid coinciding with the computational latitude-longitude grid. In the bottom half, the geographic grid (not shown) has been rotated so that the geographic poles of the earth are no longer located at the poles of the computational grid.



When WRF is to be run for a regional domain configuration, the location of the coarse domain is determined using the `ref_lat` and `ref_lon` variables, which specify the latitude and longitude, respectively, of the center of the coarse domain. If nested domains are to be processed, their locations with respect to the parent domain are specified with the `i_parent_start` and `j_parent_start` variables; further details of setting up nested domains are provided in the section on nested domains. Next, the dimensions of the coarse domain are determined by the variables `dx` and `dy`, which specify the nominal grid distance in the x-direction and y-direction, and `e_we` and `e_sn`, which give the number of velocity points (i.e., *u*-staggered or *v*-staggered points) in the x- and y-directions; for the `'lambert'`, `'mercator'`, and `'polar'` projections, `dx` and `dy` are given in meters, and for the `'lat-lon'` projection, `dx` and `dy` are given in degrees. For nested domains, only the variables `e_we` and `e_sn` are used to determine the dimensions of the grid, and `dx` and `dy` should not be specified for nests, since their values are determined recursively based on the values of the `parent_grid_ratio` and `parent_id` variables, which specify the ratio of a nest's parent grid distance to the nest's grid distance and the grid number of the nest's parent, respectively.

If the regular latitude-longitude projection will be used for a regional domain, care must be taken to ensure that the map scale factors in the region covered by the domain do not deviate significantly from unity. This can be accomplished by rotating the projection such that the area covered by the domain is located near the equator of the projection, since, for the regular latitude-longitude projection, the map scale factors in the x-direction are given by the cosine of the computational latitude. For example, in the figure above showing the unrotated and rotated earth, it can be seen that, in the rotated aspect, New Zealand is located along the computational equator, and thus, the rotation used there would be suitable for a domain covering New Zealand. As a general guideline for rotating the latitude-longitude projection for regional domains, the namelist parameters `pole_lat`, `pole_lon`, and `stand_lon` may be chosen according to the formulas in the following table.

	(`ref_lat`, `ref_lon`) in N.H.	(`ref_lat`, `ref_lon`) in S.H.
`pole_lat`	90.0 - `ref_lat`	90.0 + `ref_lat`
`pole_lon`	180.0	0.0
`stand_lon`	`-ref_lon`	`180.0 - ref_lon`

For global WRF simulations, the coverage of the coarse domain is, of course, global, so `ref_lat` and `ref_lon` do not apply, and `dx` *and* `dy` *should not be specified*, since the nominal grid distance is computed automatically based on the number of grid points. Also, it should be noted that the latitude-longitude, or cylindrical equidistant, projection (`map_proj = 'lat-lon'`) is the only projection in WRF that can support a global domain. *Nested domains within a global domain must not cover any area north of computational latitude +45 or south of computational latitude -45, since polar filters are applied poleward of these latitudes (although the cutoff latitude can be changed in the WRF namelist).*

Besides setting variables related to the projection, location, and coverage of model domains, the path to the static geographical data sets must be correctly specified with the

geog_data_path variable. Also, the user may select which resolution of static data geogrid will interpolate from using the geog_data_res variable, whose value should match one of the resolutions of data in the GEOGRID.TBL. If the full set of static data are downloaded from the WRF download page, possible resolutions include '30s', '2m', '5m', and '10m', corresponding to 30-arc-second data, 2-, 5-, and 10-arc-minute data.

Depending on the value of the wrf_core namelist variable, the appropriate GEOGRID.TBL file must be used with geogrid, since the grid staggerings that WPS interpolates to differ between dynamical cores. For the ARW, the GEOGRID.TBL.ARW file should be used, and for the NMM, the GEOGRID.TBL.NMM file should be used. Selection of the appropriate GEOGRID.TBL is accomplished by linking the correct file to GEOGRID.TBL in the geogrid directory (or in the directory specified by opt_geogrid_tbl_path, if this variable is set in the namelist).

```
> ls geogrid/GEOGRID.TBL

lrwxrwxrwx 1      15 GEOGRID.TBL -> GEOGRID.TBL.ARW
```

For more details on the meaning and possible values for each variable, the user is referred to a description of the namelist variables.

Having suitably defined the simulation coarse domain and nested domains in the namelist.wps file, the geogrid.exe executable may be run to produce domain files. In the case of ARW domains, the domain files are named geo_em.d0N.nc, where N is the number of the nest defined in each file. When run for NMM domains, geogrid produces the file geo_nmm.d01.nc for the coarse domain, and geo_nmm_nest.l0N.nc files for each nesting level N. Also, note that the file suffix will vary depending on the io_form_geogrid that is selected. To run geogrid, issue the following command:

```
> ./geogrid.exe
```

When geogrid.exe has finished running, the message

```
!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!
!  Successful completion of geogrid.          !
!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!
```

should be printed, and a listing of the WPS root directory (or the directory specified by opt_output_from_geogrid_path, if this variable was set) should show the domain files. If not, the geogrid.log file may be consulted in an attempt to determine the possible cause of failure. For more information on checking the output of geogrid, the user is referred to the section on checking WPS output.

```
> ls
drwxr-xr-x 2     4096 arch
-rwxr-xr-x 1     1672 clean
-rwxr-xr-x 1     3510 compile
-rw-r--r-- 1    85973 compile.output
-rwxr-xr-x 1     4257 configure
-rw-r--r-- 1     2486 configure.wps
-rw-r--r-- 1  1957004 geo_em.d01.nc
```

```
-rw-r--r-- 1  4745324 geo_em.d02.nc
drwxr-xr-x 4     4096 geogrid
lrwxrwxrwx 1       23 geogrid.exe -> geogrid/src/geogrid.exe
-rw-r--r-- 1    11169 geogrid.log
-rwxr-xr-x 1     1328 link_grib.csh
drwxr-xr-x 3     4096 metgrid
lrwxrwxrwx 1       23 metgrid.exe -> metgrid/src/metgrid.exe
-rw-r--r-- 1     1094 namelist.wps
-rw-r--r-- 1     1987 namelist.wps.all_options
-rw-r--r-- 1     1075 namelist.wps.global
-rw-r--r-- 1      652 namelist.wps.nmm
-rw-r--r-- 1     4786 README
drwxr-xr-x 4     4096 ungrib
lrwxrwxrwx 1       21 ungrib.exe -> ungrib/src/ungrib.exe
drwxr-xr-x 3     4096 util
```

Step 2: Extracting meteorological fields from GRIB files with ungrib

Having already downloaded meteorological data in GRIB format, the first step in extracting fields to the intermediate format involves editing the “share” and “ungrib” namelist records of the namelist.wps file – the same file that was edited to define the simulation domains. An example of the two namelist records is given below.

```
&share
 wrf_core = 'ARW',
 max_dom = 2,
 start_date = '2008-03-24_12:00:00','2008-03-24_12:00:00',
 end_date   = '2008-03-24_18:00:00','2008-03-24_12:00:00',
 interval_seconds = 21600,
 io_form_geogrid = 2
/

&ungrib
 out_format = 'WPS',
 prefix     = 'FILE'
/
```

In the “share” namelist record, the variables that are of relevance to ungrib are the starting and ending times of the coarse domain (`start_date` and `end_date`; alternatively, `start_year`, `start_month`, `start_day`, `start_hour`, `end_year`, `end_month`, `end_day`, and `end_hour`) and the interval between meteorological data files (`interval_seconds`). In the “ungrib” namelist record, the variable `out_format` is used to select the format of the intermediate data to be written by ungrib; the metgrid program can read any of the formats supported by ungrib, and thus, any of `'WPS'`, `'SI'`, and `'MM5'` may be specified for `out_format`, although `'WPS'` is recommended. Also in the "ungrib" namelist, the user may specify a path and prefix for the intermediate files with the `prefix` variable. For example, if `prefix` were set to `'ARGRMET'`, then the intermediate files created by ungrib would be named according to AGRMET:*YYYY-MM-DD_HH*, where *YYYY-MM-DD_HH* is the valid time of the data in the file.

After suitably modifying the namelist.wps file, a Vtable must be supplied, and the GRIB files must be linked (or copied) to the filenames that are expected by ungrib. The WPS is

supplied with Vtable files for many sources of meteorological data, and the appropriate Vtable may simply be symbolically linked to the file Vtable, which is the Vtable name expected by ungrib. For example, if the GRIB data are from the GFS model, this could be accomplished with

```
> ln -s ungrib/Variable_Tables/Vtable.GFS Vtable
```

The ungrib program will try to read GRIB files named GRIBFILE.AAA, GRIBFILE.AAB, …, GRIBFILE.ZZZ. In order to simplify the work of linking the GRIB files to these filenames, a shell script, link_grib.csh, is provided. The link_grib.csh script takes as a command-line argument a list of the GRIB files to be linked. For example, if the GRIB data were downloaded to the directory /data/gfs, the files could be linked with link_grib.csh as follows:

```
> ls /data/gfs
-rw-r--r-- 1  42728372 gfs_080324_12_00
-rw-r--r-- 1  48218303 gfs_080324_12_06

> ./link_grib.csh /data/gfs/gfs*
```

After linking the GRIB files and Vtable, a listing of the WPS directory should look something like the following:

```
> ls
drwxr-xr-x 2     4096 arch
-rwxr-xr-x 1     1672 clean
-rwxr-xr-x 1     3510 compile
-rw-r--r-- 1    85973 compile.output
-rwxr-xr-x 1     4257 configure
-rw-r--r-- 1     2486 configure.wps
-rw-r--r-- 1  1957004 geo_em.d01.nc
-rw-r--r-- 1  4745324 geo_em.d02.nc
drwxr-xr-x 4     4096 geogrid
lrwxrwxrwx 1       23 geogrid.exe -> geogrid/src/geogrid.exe
-rw-r--r-- 1    11169 geogrid.log
lrwxrwxrwx 1       38 GRIBFILE.AAA -> /data/gfs/gfs_080324_12_00
lrwxrwxrwx 1       38 GRIBFILE.AAB -> /data/gfs/gfs_080324_12_06
-rwxr-xr-x 1     1328 link_grib.csh
drwxr-xr-x 3     4096 metgrid
lrwxrwxrwx 1       23 metgrid.exe -> metgrid/src/metgrid.exe
-rw-r--r-- 1     1094 namelist.wps
-rw-r--r-- 1     1987 namelist.wps.all_options
-rw-r--r-- 1     1075 namelist.wps.global
-rw-r--r-- 1      652 namelist.wps.nmm
-rw-r--r-- 1     4786 README
drwxr-xr-x 4     4096 ungrib
lrwxrwxrwx 1       21 ungrib.exe -> ungrib/src/ungrib.exe
drwxr-xr-x 3     4096 util
lrwxrwxrwx 1       33 Vtable -> ungrib/Variable_Tables/Vtable.GFS
```

After editing the namelist.wps file and linking the appropriate Vtable and GRIB files, the ungrib.exe executable may be run to produce files of meteorological data in the intermediate format. Ungrib may be run by simply typing the following:

```
> ./ungrib.exe >& ungrib.output
```

Since the ungrib program may produce a significant volume of output, it is recommended that ungrib output be redirected to a file, as in the command above. If ungrib.exe runs successfully, the message

```
!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!
!  Successful completion of ungrib.          !
!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!
```

will be written to the end of the ungrib.output file, and the intermediate files should appear in the current working directory. The intermediate files written by ungrib will have names of the form `FILE:`*`YYYY-MM-DD_HH`* (unless, of course, the `prefix` variable was set to a prefix other than `'FILE'`).

```
> ls
drwxr-xr-x 2       4096 arch
-rwxr-xr-x 1       1672 clean
-rwxr-xr-x 1       3510 compile
-rw-r--r-- 1      85973 compile.output
-rwxr-xr-x 1       4257 configure
-rw-r--r-- 1       2486 configure.wps
-rw-r--r-- 1  154946888 FILE:2008-03-24_12
-rw-r--r-- 1  154946888 FILE:2008-03-24_18
-rw-r--r-- 1    1957004 geo_em.d01.nc
-rw-r--r-- 1    4745324 geo_em.d02.nc
drwxr-xr-x 4       4096 geogrid
lrwxrwxrwx 1         23 geogrid.exe -> geogrid/src/geogrid.exe
-rw-r--r-- 1      11169 geogrid.log
lrwxrwxrwx 1         38 GRIBFILE.AAA -> /data/gfs/gfs_080324_12_00
lrwxrwxrwx 1         38 GRIBFILE.AAB -> /data/gfs/gfs_080324_12_06
-rwxr-xr-x 1       1328 link_grib.csh
drwxr-xr-x 3       4096 metgrid
lrwxrwxrwx 1         23 metgrid.exe -> metgrid/src/metgrid.exe
-rw-r--r-- 1       1094 namelist.wps
-rw-r--r-- 1       1987 namelist.wps.all_options
-rw-r--r-- 1       1075 namelist.wps.global
-rw-r--r-- 1        652 namelist.wps.nmm
-rw-r--r-- 1       4786 README
drwxr-xr-x 4       4096 ungrib
lrwxrwxrwx 1         21 ungrib.exe -> ungrib/src/ungrib.exe
-rw-r--r-- 1       1418 ungrib.log
-rw-r--r-- 1      27787 ungrib.output
drwxr-xr-x 3       4096 util
lrwxrwxrwx 1         33 Vtable ->
ungrib/Variable_Tables/Vtable.GFS
```

Step 3: Horizontally interpolating meteorological data with metgrid

In the final step of running the WPS, meteorological data extracted by ungrib are horizontally interpolated to the simulation grids defined by geogrid. In order to run metgrid, the namelist.wps file must be edited. In particular, the “share” and “metgrid” namelist records are of relevance to the metgrid program. Examples of these records are shown below.

```
&share
 wrf_core = 'ARW',
 max_dom = 2,
 start_date = '2008-03-24_12:00:00','2008-03-24_12:00:00',
 end_date   = '2008-03-24_18:00:00','2008-03-24_12:00:00',
 interval_seconds = 21600,
 io_form_geogrid = 2
/

&metgrid
 fg_name                         = 'FILE',
 io_form_metgrid                 = 2,
/
```

By this point, there is generally no need to change any of the variables in the “share” namelist record, since those variables should have been suitably set in previous steps. If the "share" namelist was not edited while running geogrid and ungrib, however, the WRF dynamical core, number of domains, starting and ending times, interval between meteorological data, and path to the static domain files must be set in the “share” namelist record, as described in the steps to run geogrid and ungrib.

In the “metgrid” namelist record, the path and prefix of the intermediate meteorological data files must be given with `fg_name`, the full path and file names of any intermediate files containing constant fields may be specified with the `constants_name` variable, and the output format for the horizontally interpolated files may be specified with the `io_form_metgrid` variable. Other variables in the “metgrid” namelist record, namely, `opt_output_from_metgrid_path` and `opt_metgrid_tbl_path`, allow the user to specify where interpolated data files should be written by metgrid and where the METGRID.TBL file may be found.

As with geogrid and the GEOGRID.TBL file, a METGRID.TBL file appropriate for the WRF core must be linked in the metgrid directory (or in the directory specified by `opt_metgrid_tbl_path`, if this variable is set).

```
> ls metgrid/METGRID.TBL

lrwxrwxrwx 1      15 METGRID.TBL -> METGRID.TBL.ARW
```

After suitably editing the namelist.wps file and verifying that the correct METGRID.TBL will be used, metgrid may be run by issuing the command

```
> ./metgrid.exe
```

If metgrid successfully ran, the message

```
!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!
!  Successful completion of metgrid.        !
!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!
```

will be printed. After successfully running, metgrid output files should appear in the WPS root directory (or in the directory specified by `opt_output_from_metgrid_path`, if this variable was set). These files will be named `met_em.d0N.YYYY-MM-DD_HH:mm:ss.nc` in

the case of ARW domains, where `N` is the number of the nest whose data reside in the file, or `met_nmm.d01.YYYY-MM-DD_HH:mm:ss.nc` in the case of NMM domains. Here, `YYYY-MM-DD_HH:mm:ss` refers to the date of the interpolated data in each file. If these files do not exist for each of the times in the range given in the "share" namelist record, the metgrid.log file may be consulted to help in determining the problem in running metgrid.

```
      > ls
      drwxr-xr-x 2       4096 arch
      -rwxr-xr-x 1       1672 clean
      -rwxr-xr-x 1       3510 compile
      -rw-r--r-- 1      85973 compile.output
      -rwxr-xr-x 1       4257 configure
      -rw-r--r-- 1       2486 configure.wps
      -rw-r--r-- 1  154946888 FILE:2008-03-24_12
      -rw-r--r-- 1  154946888 FILE:2008-03-24_18
      -rw-r--r-- 1    1957004 geo_em.d01.nc
      -rw-r--r-- 1    4745324 geo_em.d02.nc
      drwxr-xr-x 4       4096 geogrid
      lrwxrwxrwx 1         23 geogrid.exe -> geogrid/src/geogrid.exe
      -rw-r--r-- 1      11169 geogrid.log
      lrwxrwxrwx 1         38 GRIBFILE.AAA -> /data/gfs/gfs_080324_12_00
      lrwxrwxrwx 1         38 GRIBFILE.AAB -> /data/gfs/gfs_080324_12_06
      -rwxr-xr-x 1       1328 link_grib.csh
      -rw-r--r-- 1    5217648 met_em.d01.2008-03-24_12:00:00.nc
      -rw-r--r-- 1    5217648 met_em.d01.2008-03-24_18:00:00.nc
      -rw-r--r-- 1   12658200 met_em.d02.2008-03-24_12:00:00.nc
      drwxr-xr-x 3       4096 metgrid
      lrwxrwxrwx 1         23 metgrid.exe -> metgrid/src/metgrid.exe
      -rw-r--r-- 1      65970 metgrid.log
      -rw-r--r-- 1       1094 namelist.wps
      -rw-r--r-- 1       1987 namelist.wps.all_options
      -rw-r--r-- 1       1075 namelist.wps.global
      -rw-r--r-- 1        652 namelist.wps.nmm
      -rw-r--r-- 1       4786 README
      drwxr-xr-x 4       4096 ungrib
      lrwxrwxrwx 1         21 ungrib.exe -> ungrib/src/ungrib.exe
      -rw-r--r-- 1       1418 ungrib.log
      -rw-r--r-- 1      27787 ungrib.output
      drwxr-xr-x 3       4096 util
      lrwxrwxrwx 1         33 Vtable ->
ungrib/Variable_Tables/Vtable.GFS
```

Creating Nested Domains with the WPS

To run the WPS for nested-domain simulations is essentially no more difficult than running for a single-domain case; the difference with nested-domain simulations is that the geogrid and metgrid programs process more than one grid when they are run, rather than a single grid for the simulation. In order to specify the size and location of nests, a number of variables in the namelist.wps file must be given lists of values, one value per nest.

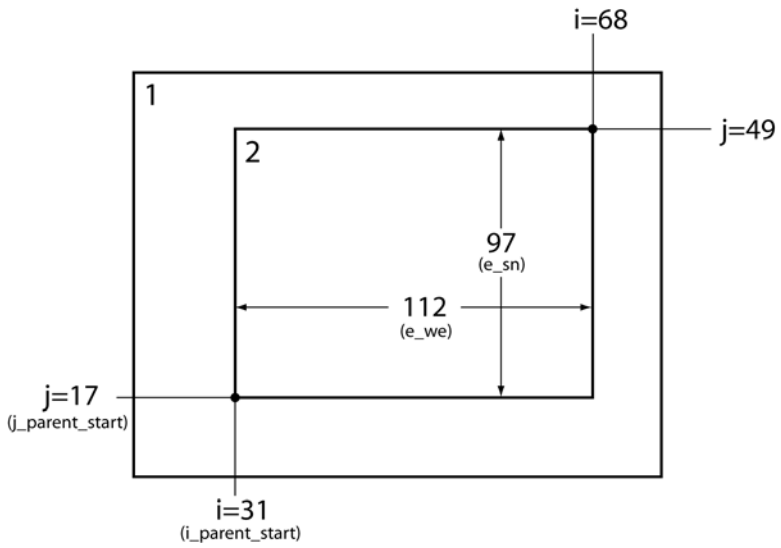
```
&share
 wrf_core = 'ARW',
 max_dom = 2,
 start_date = '2008-03-24_12:00:00','2008-03-24_12:00:00',
 end_date   = '2008-03-24_18:00:00','2008-03-24_12:00:00',
 interval_seconds = 21600,
 io_form_geogrid = 2
/

&geogrid
 parent_id         =   1,   1,
 parent_grid_ratio =   1,   3,
 i_parent_start    =   1,  31,
 j_parent_start    =   1,  17,
 s_we              =   1,   1,
 e_we              =  74, 112,
 s_sn              =   1,   1,
 e_sn              =  61,  97,
 geog_data_res     = '10m','2m',
 dx = 30000,
 dy = 30000,
 map_proj = 'lambert',
 ref_lat   = 34.83,
 ref_lon   = -81.03,
 truelat1  =  30.0,
 truelat2  =  60.0,
 stand_lon = -98.
 geog_data_path = '/mmm/users/wrfhelp/WPS_GEOG/'
/
```

The namelist variables that are affected by nests are shown in the (partial) namelist records above. The example shows namelist variables for a two-domain run (the coarse domain plus a single nest), and the effect on the namelist variables generalize to multiple nests in the obvious way: rather than specifying lists of two values, lists of *N* values must be specified, where *N* is the total number of model grids.

In the above example, the first change to the "share" namelist record is to the `max_dom` variable, which must be set to the total number of nests in the simulation, including the coarse domain. Having determined the number of nests, all of the other affected namelist variables must be given a list of *N* values, one for each grid. The only other change to the "share" namelist record is to the starting and ending times. Here, a starting and ending time must be given for each nest, with the restriction that a nest cannot begin before its parent domain or end after its parent domain; also, it is suggested that nests be given starting and ending times that are identical to the desired starting times of the nest *when running WPS*. This is because the nests get their lateral boundary conditions from their parent domain, and thus, only the initial time for a nest needs to be processed by WPS, except when grid nudging, also called analysis nudging, is used in WRF. It is important to note that, *when running WRF*, the actual starting and ending times for all nests must be given in the WRF namelist.input file.

The remaining changes are to the "geogrid" namelist record. In this record, the parent of each nest must be specified with the `parent_id` variable. Every nest must be a child of exactly one other nest, with the coarse domain being its own parent. Related to the identity of a nest's parent is the nest refinement ratio with respect to its parent, which is

given by the `parent_grid_ratio` variable; this ratio determines the nominal grid spacing for a nest in relation to the grid spacing of the its parent.



Next, the lower-left corner of a nest is specified as an (i, j) location in the nest's parent domain; this is done through the `i_parent_start` and `j_parent_start` variables, and the specified location is given with respect to the unstaggered grid. Finally, the dimensions of each nest, in grid points, are given for each nest using the `s_we`, `e_we`, `s_sn`, and `e_sn` variables. The nesting setup in our example namelist is illustrated in the figure above, where it may be seen how each of the above-mentioned variables is determined. Currently, the starting grid point values in the south-north (`s_sn`) and west-east (`s_we`) directions must be specified as 1, and the ending grid point values (`e_sn` and `e_we`) determine, essentially, the full dimensions of the nest; to ensure that the upper-right corner of the nest's grid is coincident with an unstaggered grid point in the parent domain, both `e_we` and `e_sn` must be one greater than some integer multiple of the nesting ratio. Also, for each nest, the resolution (or list or resolutions; see the description of namelist variables) of source data to interpolate from is specified with the `geog_data_res` variable. For a complete description of these namelist variables, the user is referred to the description of namelist variables.

Selecting Between USGS and MODIS-based Land Use Classifications

By default, the geogrid program will interpolate land use categories from USGS 24-category data. However, the user may select an alternative set of land use categories based on the MODIS land-cover classification of the International Geosphere-Biosphere Programme and modified for the Noah land surface model. Although the MODIS-based data contain 20 categories of land use, these categories are not a subset of the 24 USGS categories; users interested in the specific categories in either data set can find a listing of the land use classes in the section on land use and soil categories. *It must be emphasized*

that the MODIS-based categories should only be used with the Noah land surface model in WRF.

The 20-category MODIS-based land use data may be selected instead of the USGS data at run-time through the `geog_data_res` variable in the "geogrid" namelist record. This is accomplished by prefixing each resolution of static data with the string "modis_30s+". For example, in a three-domain configuration, where the `geog_data_res` variable would ordinarily be specified as

```
geog_data_res = '10m', '2m', '30s'
```

the user should instead specify

```
geog_data_res = 'modis_30s+10m', 'modis_30s+2m', 'modis_30s+30s'
```

The effect of this change is to instruct the geogrid program to look, in each entry of the GEOGRID.TBL file, for a resolution of static data with a resolution denoted by 'modis_30s', and if such a resolution is not available, to instead look for a resolution denoted by the string following the '+'. Thus, for the GEOGRID.TBL entry for the LANDUSEF field, the MODIS-based land use data, which is identified with the string 'modis_30s', would be used instead of the '10m', '2m', and '30s' resolutions of USGS data in the example above; for all other fields, the '10m', '2m', and '30s' resolutions would be used for the first, second, and third domains, respectively. As an aside, when none of the resolutions specified for a domain in `geog_data_res` are found in a GEOGRID.TBL entry, the resolution denoted by 'default' will be used.

Selecting Static Data for the Gravity Wave Drag Scheme

The gravity wave drag by orography (GWDO) scheme in the ARW requires ten static fields from the WPS. In fact, these fields will be interpolated by the geogrid program regardless of whether the GWDO scheme will be used in the model. When the GWDO scheme will not be used, the fields will simply be ignored in WRF, and the user need not be concerned with the resolution of data from which the fields are interpolated. However, it is recommended that these fields be interpolated from a resolution of source data that is slightly *lower* (i.e., coarser) in resolution than the model grid; consequently, if the GWDO scheme will be used, care should be taken to select an appropriate resolution of GWDO static data. Currently, five resolutions of GWDO static data are available: 2-degree, 1-degree, 30-minute, 20-minute, and 10-minute, denoted by the strings '2deg', '1deg', '30m', '20m', and '10m', respectively. To select the resolution to interpolate from, the user should prefix the resolution specified for the `geog_data_res` variable in the "geogrid" namelist record by the string "XXX+", where XXX is one of the five available resolutions of GWDO static data. For example, in a model configuration with a 48-km grid spacing, the `geog_data_res` variable might typically be specified as

```
geog_data_res = '10m',
```

However, if the GWDO scheme were employed, the finest resolution of GWDO static data that is still lower in resolution than the model grid would be the 30-minute data, in which case the user should specify

```
geog_data_res = '30m+10m',
```

If none of '2deg', '1deg', '30m', or '20m' are specified in combination with other resolutions of static data in the `geog_data_res` variable, the '10m' GWDO static data will be used, since it is also designated as the 'default' resolution in the GEOGRID.TBL file. It is worth noting that, if 10-minute resolution GWDO data are to be used, but a different resolution is desired for other static fields (e.g., topography height), the user should simply omit '10m' from the value given to the `geog_data_res` variable, since specifying

```
geog_data_res = '10m+30s',
```

for example, would cause geogrid to use the 10-mintute data in preference to the 30-second data for the non-GWDO fields, such as topography height and land use category, as well as for the GWDO fields.

Using Multiple Meteorological Data Sources

The metgrid program is capable of interpolating time-invariant fields, and it can also interpolate from multiple sources of meteorological data. The first of these capabilities uses the `constants_name` variable in the `&metgrid` namelist record. This variable may be set to a list of filenames – including path information where necessary – of intermediate-formatted files which contains time-invariant fields, and which should be used in the output for every time period processed by metgrid. For example, short simulations may use a constant SST field; this field need only be available at a single time, and may be used by setting the `constants_name` variable to the path and filename of the SST intermediate file. Typical uses of `constants_name` might look like

```
&metgrid
 constants_name = '/data/ungribbed/constants/SST_FILE:2006-08-16_12'
/
```

or

```
&metgrid
 constants_name = 'LANDSEA', 'SOILHGT'
/
```

The second metgrid capability – that of interpolating data from multiple sources – may be useful in situations where two or more complementary data sets need to be combined to produce the full input data needed by real.exe. To interpolate from multiple sources of time-varying, meteorological data, the `fg_name` variable in the `&metgrid` namelist record

should be set to a list of prefixes of intermediate files, including path information when necessary. When multiple path-prefixes are given, and the same meteorological field is available from more than one of the sources, data from the last-specified source will take priority over all preceding sources. Thus, data sources may be prioritized by the order in which the sources are given.

As an example of this capability, if surface fields are given in one data source and upper-air data are given in another, the values assigned to the `fg_name` variable may look something like:

```
&metgrid
 fg_name = '/data/ungribbed/SFC', '/data/ungribbed/UPPER_AIR'
/
```

To simplify the process of extracting fields from GRIB files, the `prefix` namelist variable in the `&ungrib` record may be employed. This variable allows the user to control the names of (and paths to) the intermediate files that are created by ungrib. The utility of this namelist variable is most easily illustrated by way of an example. Suppose we wish to work with the North American Regional Reanalysis (NARR) data set, which is split into separate GRIB files for 3-dimensional atmospheric data, surface data, and fixed-field data. We may begin by linking all of the "3D" GRIB files using the `link_grib.csh` script, and by linking the NARR Vtable to the filename `Vtable`. Then, we may suitably edit the `&ungrib` namelist record before running ungrib.exe so that the resulting intermediate files have an appropriate prefix:

```
&ungrib
 out_format = 'WPS',
 prefix = 'NARR_3D',
/
```

After running ungrib.exe, the following files should exist (with a suitable substitution for the appropriate dates):

```
NARR_3D:2008-08-16_12
NARR_3D:2008-08-16_15
NARR_3D:2008-08-16_18
...
```

Given intermediate files for the 3-dimensional fields, we may process the surface fields by linking the surface GRIB files and changing the `prefix` variable in the namelist:

```
&ungrib
 out_format = 'WPS',
 prefix = 'NARR_SFC',
/
```

Again running ungrib.exe, the following should exist in addition to the NARR_3D files:

```
NARR_SFC:2008-08-16_12
NARR_SFC:2008-08-16_15
NARR_SFC:2008-08-16_18
...
```

Finally, the fixed file is linked with the `link_grib.csh` script, and the `prefix` variable in the namelist is again set:

```
&ungrib
 out_format = 'WPS',
 prefix = 'NARR_FIXED',
/
```

Having run ungrib.exe for the third time, the fixed fields should be available in addition to the surface and "3D" fields:

```
NARR_FIXED:1979-11-08_00
```

For the sake of clarity, the fixed file may be renamed to remove any date information, for example, by renaming it to simply `NARR_FIXED`, since the fields in the file are static. In this example, we note that the NARR fixed data are only available at a specific time, 1979 November 08 at 0000 UTC, and thus, the user would need to set the correct starting and ending time for the data in the `&share` namelist record before running ungrib on the NARR fixed file; of course, the times should be re-set before metgrid is run.

Given intermediate files for all three parts of the NARR data set, metgrid.exe may be run after the `constants_name` and `fg_name` variables in the `&metgrid` namelist record are set:

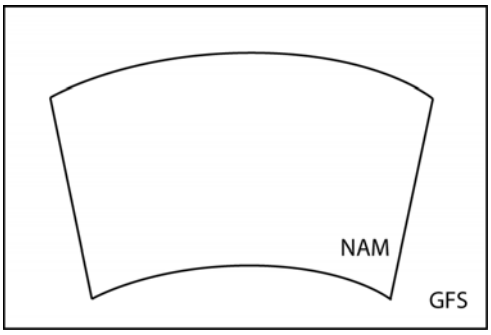
```
&metgrid
 constants_name = 'NARR_FIXED',
 fg_name = 'NARR_3D', 'NARR_SFC'
/
```

Although less common, another situation where multiple data sources would be required is when a source of meteorological data from a regional model is insufficient to cover the entire simulation domain, and data from a larger regional model, or a global model, must be used when interpolating to the remaining points of the simulation grid.

For example, to use NAM data wherever possible, and GFS data elsewhere, the following values might be assigned in the namelist:

```
&metgrid
 fg_name = '/data/ungribbed/GFS', '/data/ungribbed/NAM'
/
```

Then the resulting model domain would use data as shown in the figure below.



If no field is found in more than one source, then no prioritization need be applied by metgrid, and each field will simply be interpolated as usual; of course, each source should cover the entire simulation domain to avoid areas of missing data.

Parallelism in the WPS

If the dimensions of the domains to be processed by the WPS become too large to fit in the memory of a single CPU, it is possible to run the geogrid and metgrid programs in a distributed memory configuration. In order to compile geogrid and metgrid for distributed memory execution, the user must have MPI libraries installed on the target machine, and must have compiled WPS using one of the "DM parallel" configuration options. Upon successful compilation, the geogrid and metgrid programs may be run with the *mpirun* or *mpiexec* commands, or through a batch queuing system, depending on the machine.

As mentioned earlier, the work of the ungrib program is not amenable to parallelization, and, further, the memory requirements for ungrib's processing are independent of the memory requirements of geogrid and metgrid; thus, ungrib is always compiled for a single processor and run on a single CPU, regardless of whether a "DM parallel" configuration option was selected during configuration.

Each of the standard WRF I/O API formats (NetCDF, GRIB1, binary) has a corresponding parallel format, whose number is given by adding 100 to the io_form value (i.e., the value of `io_form_geogrid` and `io_form_metgrid`) for the standard format. It is not necessary to use a parallel io_form, but when one is used, each CPU will read/write its input/output to a separate file, whose name is simply the name that would be used during serial execution, but with a four-digit processor ID appended to the name. For example, running geogrid on four processors with `io_form_geogrid=102` would create output files named geo_em.d01.nc.0000, geo_em.d01.nc.0001, geo_em.d01.nc.0002, and geo_em.d01.nc.0003 for the coarse domain.

During distributed-memory execution, model domains are decomposed into rectangular patches, with each processor working on a single patch. When reading/writing from/to

the WRF I/O API format, each processor reads/writes only its patch. Consequently, if a parallel io_form is chosen for the output of geogrid, metgrid must be run using the same number of processors as were used to run geogrid. Similarly, if a parallel io_form is chosen for the metgrid output files, the real program must be run using the same number of processors. Of course, it is still possible to use a standard io_form when running on multiple processors, in which case all data for the model domain will be distributed/collected upon input/output. As a final note, when geogrid or metgrid are run on multiple processors, each processor will write its own log file, with the log file names being appended with the same four-digit processor ID numbers that are used for the I/O API files.

Checking WPS Output

When running the WPS, it may be helpful to examine the output produced by the programs. For example, when determining the location of nests, it may be helpful to see the interpolated static geographical data and latitude/longitude fields. As another example, when importing a new source of data into WPS – either static data or meteorological data – it can often be helpful to check the resulting interpolated fields in order to make adjustments the interpolation methods used by geogrid or metgrid.

By using the NetCDF format for the geogrid and metgrid I/O forms, a variety of visualization tools that read NetCDF data may be used to check the domain files processed by geogrid or the horizontally interpolated meteorological fields produced by metgrid. In order to set the file format for geogrid and metgrid to NetCDF, the user should specify 2 as the `io_form_geogrid` and `io_form_metgrid` in the WPS namelist file (Note: 2 is the default setting for these options):

```
&share
 io_form_geogrid = 2,
/

&metgrid
 io_form_metgrid = 2,
/
```

Among the available tools, the ncdump, ncview, and new RIP4 programs may be of interest. The ncdump program is a compact utility distributed with the NetCDF libraries that lists the variables and attributes in a NetCDF file. This can be useful, in particular, for checking the domain parameters (e.g., west-east dimension, south-north dimension, or domain center point) in geogrid domain files, or for listing the fields in a file. The ncview program provides an interactive way to view fields in NetCDF files. Also, for users wishing to produce plots of fields suitable for use in publications, the new release of the RIP4 program may be of interest. The new RIP4 is capable of plotting horizontal contours, map backgrounds, and overlaying multiple fields within the same plot.

Output from the ungrib program is always written in a simple binary format (either 'WPS', 'SI', or 'MM5'), so software for viewing NetCDF files will almost certainly be of no use. However, an NCAR Graphics-based utility, *plotfmt*, is supplied with the WPS source code. This utility produces contour plots of the fields found in an intermediate-format file. If the NCAR Graphics libraries are properly installed, the plotfmt program is automatically compiled, along with other utility programs, when WPS is built.

WPS Utility Programs

Besides the three main WPS programs – geogrid, ungrib, and metgrid – there are a number of utility programs that come with the WPS, and which are compiled in the util directory. These utilities may be used to examine data files, visualize the location of nested domains, compute pressure fields, and compute average surface temperature fields.

A. avg_tsfc.exe

The avg_tsfc.exe program computes a daily mean surface temperature given input files in the intermediate format. Based on the range of dates specified in the "share" namelist section of the namelist.wps file, and also considering the interval between intermediate files, avg_tsfc.exe will use as many complete days' worth of data as possible in computing the average, beginning at the starting date specified in the namelist. If a complete day's worth of data is not available, no output file will be written, and the program will halt as soon as this can be determined. Similarly, any intermediate files for dates that cannot be used as part of a complete 24-hour period are ignored; for example, if there are five intermediate files available at a six-hour interval, the last file would be ignored. The computed average field is written to a new file named TAVGSFC using the same intermediate format version as the input files. This daily mean surface temperature field can then be ingested by metgrid by specifying 'TAVGSFC' for the `constants_name` variable in the "metgrid" namelist section.

B. mod_levs.exe

The mod_levs.exe program is used to remove levels of data from intermediate format files. The levels which are to be kept are specified in new namelist record in the namelist.wps file:

```
&mod_levs
 press_pa = 201300 , 200100 , 100000 ,
             95000 ,  90000 ,
             85000 ,  80000 ,
             75000 ,  70000 ,
             65000 ,  60000 ,
             55000 ,  50000 ,
             45000 ,  40000 ,
             35000 ,  30000 ,
             25000 ,  20000 ,
```

```
             15000 ,  10000 ,
              5000 ,   1000
/
```

Within the `&mod_levs` namelist record, the variable `press_pa` is used to specify a list of levels to keep; the specified levels should match values of `xlvl` in the intermediate format files (see the discussion of the WPS intermediate format for more information on the fields of the intermediate files). The mod_levs program takes two command-line arguments as its input. The first argument is the name of the intermediate file to operate on, and the second argument is the name of the output file to be written.

Removing all but a specified subset of levels from meteorological data sets is particularly useful, for example, when one data set is to be used for the model initial conditions and a second data set is to be used for the lateral boundary conditions. This can be done by providing the initial conditions data set at the first time period to be interpolated by metgrid, and the boundary conditions data set for all other times. If the both data sets have the same number of vertical levels, then no work needs to be done; however, when these two data sets have a different number of levels, it will be necessary, at a minimum, to remove ($m - n$) levels, where $m > n$ and m and n are the number of levels in each of the two data sets, from the data set with m levels. The necessity of having the same number of vertical levels in all files is due to a limitation in real.exe, which requires a constant number of vertical levels to interpolate from.

The mod_levs utility is something of a temporary solution to the problem of accommodating two or more data sets with differing numbers of vertical levels. Should a user choose to use mod_levs, it should be noted that, although the vertical locations of the levels need not match between data sets, all data sets should have a surface level of data, and, when running real.exe and wrf.exe, the value of `p_top` must be chosen to be below the lowest top among the data sets.

C. calc_ecmwf_p.exe

In the course of vertically interpolating meteorological fields, the real program requires 3-d pressure and geopotential height fields on the same levels as the other atmospheric fields. The calc_ecmwf_p.exe utility may be used to create such these fields for use with ECMWF sigma-level data sets. Given a surface pressure field (or log of surface pressure field) and a list of coefficients A and B, calc_ecmwf_p.exe computes the pressure at an ECMWF sigma level k at grid point (i,j) as $P_{ijk} = A_k + B_k * Psfc_{ij}$. The list of coefficients used in the pressure computation can be copied from a table appropriate to the number of sigma levels in the data set from http://www.ecmwf.int/products/data/technical/model_levels/index.html. This table should be written in plain text to a file, ecmwf_coeffs, in the current working directory; for example, with 16 sigma levels, the file emcwf_coeffs would contain something like:

```
    0          0.000000      0.000000000
    1       5000.000000      0.000000000
    2       9890.519531      0.001720764
    3      14166.304688      0.013197623
    4      17346.066406      0.042217135
```

```
 5     19121.152344      0.093761623
 6     19371.250000      0.169571340
 7     18164.472656      0.268015683
 8     15742.183594      0.384274483
 9     12488.050781      0.510830879
10      8881.824219      0.638268471
11      5437.539063      0.756384850
12      2626.257813      0.855612755
13       783.296631      0.928746223
14         0.000000      0.972985268
15         0.000000      0.992281914
16         0.000000      1.000000000
```

Additionally, if soil height (or soil geopotential), 3-d temperature, and 3-d specific humidity fields are available, calc_ecmwf_p.exe computes a 3-d geopotential height field, which is required to obtain an accurate vertical interpolation in the real program.

Given a set of intermediate files produced by ungrib and the file ecmwf_coeffs, calc_ecmwf_p loops over all time periods in namelist.wps, and produces an additional intermediate file, PRES:*YYYY-MM-DD_HH*, for each time, which contains pressure and geopotential height data for each full sigma level, as well as a 3-d relative humidity field. This intermediate file should be specified to metgrid, along with the intermediate data produced by ungrib, by adding 'PRES' to the list of prefixes in the `fg_name` namelist variable.

D. height_ukmo.exe

The real program requires 3-d pressure and geopotential height fields to vertically interpolate the output of the metgrid program; however, data sets from the UKMO Unified Model contain a 3-d pressure field, but do not contain a geopotential height field. Accordingly, the height_ukmo.exe program may be used to compute a geopotential height field for data sets from the UKMO Unified Model. The height_ukmo.exe program requires no command-line arguments, but reads the `&metgrid` namelist record to get the prefix of the intermediate files created by ungrib.exe; the intermediate files indicated by the first prefix in the `fg_name` variable of the `&metgrid` namelist record are expected to contain a SOILHGT field, from which the height_ukmo.exe program computes, with the aid of an auxiliary table, the 3-d geopotential height field. The computed height field is written to a new intermediate file with the prefix HGT, and the prefix ‘HGT’ should then be added to the `fg_name` namelist variable in the `&metgrid` namelist record before running metgrid.exe. The name of the file containing the auxiliary table is currently hard-wired in the source code of the height_ukmo.exe program, and it is the responsibility of the user to change this file name in WPS/util/src/height_ukmo.F to the name of the table with the same number of levels as the GRIB data processed by ungrib.exe; tables for data with 38, 50, and 70 levels are provided in the WPS/util directory with file names vertical_grid_38_20m_G3.txt, vertical_grid_50_20m_63km.txt , and vertical_grid_70_20m_80km.txt, respectively.

E. plotgrids.exe

The plotgrids.exe program is an NCAR Graphics-based utility whose purpose is to plot the locations of all nests defined in the namelist.wps file. The program operates on the namelist.wps file, and thus, may be run without having run any of the three main WPS programs. Upon successful completion, plotgrids produces an NCAR Graphics metafile, gmeta, which may be viewed using the idt command. The coarse domain is drawn to fill the plot frame, a map outline with political boundaries is drawn over the coarse domain, and any nested domains are drawn as rectangles outlining the extent of each nest. This utility may be useful particularly during initial placement of domains, at which time the user can iteratively adjust the locations of nests by editing the namelist.wps file, running plotgrids.exe, and determining a set of adjustments to the nest locations. *Currently, this utility does not work for ARW domains that use the latitude-longitude projection* (i.e., when `map_proj = 'lat-lon'`).

F. g1print.exe

The g1print.exe program takes as its only command-line argument the name of a GRIB Edition 1 file. The program prints a listing of the fields, levels, and dates of the data in the file.

G. g2print.exe

Similar to g1print.exe, the g2print.exe program takes as its only command-line argument the name of a GRIB Edition 2 file. The program prints a listing of the fields, levels, and dates of the data in the file.

H. plotfmt.exe

The plotfmt.exe is an NCAR Graphics program that plots the contents of an intermediate format file. The program takes as its only command-line argument the name of the file to plot, and produces an NCAR Graphics metafile, which contains contour plots of each field in input file. The graphics metafile output, gmeta, may be viewed with the idt command, or converted to another format using utilities such as ctrans.

I. rd_intermediate.exe

Given the name of a singe intermediate format file on the command line, the rd_intermediate.exe program prints information about the fields contained in the file.

Writing Meteorological Data to the Intermediate Format

The role of the ungrib program is to decode GRIB data sets into a simple intermediate format that is understood by metgrid. If meteorological data are not available in GRIB

Edition 1 or GRIB Edition 2 formats, the user is responsible for writing such data into the intermediate file format. Fortunately, the intermediate format is relatively simple, consisting of a sequence of unformatted Fortran writes. It is important to note that these *unformatted writes use big-endian byte order*, which can typically be specified with compiler flags. Below, we describe the WPS intermediate format; users interested in the SI or MM5 intermediate formats can first gain familiarity with the WPS format, which is very similar, and later examine the Fortran subroutines that read and write all three intermediate formats (metgrid/src/read_met_module.F90 and metgrid/src/write_met_module.F90, respectively).

When writing data to the WPS intermediate format, 2-dimensional fields are written as a rectangular array of real values. 3-dimensional arrays must be split across the vertical dimension into 2-dimensional arrays, which are written independently. It should also be noted that, for global data sets, either a Gaussian or cylindrical equidistant projection must be used, and for regional data sets, either a Mercator, Lambert conformal, polar stereographic, or cylindrical equidistant may be used. The sequence of writes used to write a single 2-dimensional array in the WPS intermediate format is as follows (note that not all of the variables declared below are used for a given projection of the data).

```
integer :: version             ! Format version (must =5 for WPS format)
integer :: nx, ny              ! x- and y-dimensions of 2-d array
integer :: iproj               ! Code for projection of data in array:
                               !      0 = cylindrical equidistant
                               !      1 = Mercator
                               !      3 = Lambert conformal conic
                               !      4 = Gaussian (global only!)
                               !      5 = Polar stereographic
real :: nlats                  ! Number of latitudes north of equator
                               !      (for Gaussian grids)
real :: xfcst                  ! Forecast hour of data
real :: xlvl                   ! Vertical level of data in 2-d array
real :: startlat, startlon     ! Lat/lon of point in array indicated by
                               !      startloc string
real :: deltalat, deltalon     ! Grid spacing, degrees
real :: dx, dy                 ! Grid spacing, km
real :: xlonc                  ! Standard longitude of projection
real :: truelat1, truelat2     ! True latitudes of projection
real :: earth_radius           ! Earth radius, km
real, dimension(nx,ny) :: slab ! The 2-d array holding the data
logical :: is_wind_grid_rel    ! Flag indicating whether winds are
                               !      relative to source grid (TRUE) or
                               !      relative to earth (FALSE)
character (len=8)  :: startloc ! Which point in array is given by
                               !      startlat/startlon; set either
                               !      to 'SWCORNER' or 'CENTER  '
character (len=9)  :: field    ! Name of the field
character (len=24) :: hdate    ! Valid date for data YYYY:MM:DD_HH:00:00
character (len=25) :: units    ! Units of data
character (len=32) :: map_source  !  Source model / originating center
character (len=46) :: desc     ! Short description of data


!  1) WRITE FORMAT VERSION
write(unit=ounit) version

!  2) WRITE METADATA
! Cylindrical equidistant
```

```
if (iproj == 0) then
      write(unit=ounit) hdate, xfcst, map_source, field, &
                        units, desc, xlvl, nx, ny, iproj
      write(unit=ounit) startloc, startlat, startlon, &
                        deltalat, deltalon, earth_radius

! Mercator
else if (iproj == 1) then
      write(unit=ounit) hdate, xfcst, map_source, field, &
                        units, desc, xlvl, nx, ny, iproj
      write(unit=ounit) startloc, startlat, startlon, dx, dy, &
                        truelat1, earth_radius

! Lambert conformal
else if (iproj == 3) then
      write(unit=ounit) hdate, xfcst, map_source, field, &
                        units, desc, xlvl, nx, ny, iproj
      write(unit=ounit) startloc, startlat, startlon, dx, dy, &
                        xlonc, truelat1, truelat2, earth_radius

! Gaussian
else if (iproj == 4) then
      write(unit=ounit) hdate, xfcst, map_source, field, &
                        units, desc, xlvl, nx, ny, iproj
      write(unit=ounit) startloc, startlat, startlon, &
                              nlats, deltalon, earth_radius

! Polar stereographic
else if (iproj == 5) then
      write(unit=ounit) hdate, xfcst, map_source, field, &
                        units, desc, xlvl, nx, ny, iproj
      write(unit=ounit) startloc, startlat, startlon, dx, dy, &
                        xlonc, truelat1, earth_radius

end if

!  3) WRITE WIND ROTATION FLAG
write(unit=ounit) is_wind_grid_rel

!  4) WRITE 2-D ARRAY OF DATA
write(unit=ounit) slab
```

Creating and Editing Vtables

Although Vtables are provided for many common data sets, it would be impossible for ungrib to anticipate every possible source of meteorological data in GRIB format. When a new source of data is to be processed by ungrib.exe, the user may create a new Vtable either from scratch, or by using an existing Vtable as an example. In either case, a basic knowledge of the meaning and use of the various fields of the Vtable will be helpful.

Each Vtable contains either seven or eleven fields, depending on whether the Vtable is for a GRIB Edition 1 data source or a GRIB Edition 2 data source, respectively. The fields of a Vtable fall into one of three categories: fields that describe how the data are identified within the GRIB file, fields that describe how the data are identified by the ungrib and metgrid programs, and fields specific to GRIB Edition 2. Each variable to be extracted by ungrib.exe will have one or more lines in the Vtable, with multiple lines for

data that are split among different level types – for example, a surface level and upper-air levels. The fields that must be specified for a line, or entry, in the Vtable depends on the specifics of the field and level.

The first group of fields – those that describe how the data are identified within the GRIB file – are given under the column headings of the Vtable shown below.

```
GRIB1| Level| From |  To  |
Param| Type |Level1|Level2|
-----+------+------+------+
```

The "GRIB1 Param" field specifies the GRIB code for the meteorological field, which is a number unique to that field within the data set. However, different data sets may use different GRIB codes for the same field – for example, temperature at upper-air levels has GRIB code 11 in GFS data, but GRIB code 130 in ECMWF data. To find the GRIB code for a field, the g1print.exe and g2print.exe utility program may be used.

Given a GRIB code, the "Level Type", "From Level1", and "From Level2" fields are used to specify which levels a field may be found at. As with the "GRIB1 Param" field, the g1print.exe and g2print.exe programs may be used to find values for the level fields. The meanings of the level fields are dependent on the "Level Type" field, and are summarized in the following table.

Level	Level Type	From Level1	To Level2
Upper-air	100	*	(blank)
Surface	1	0	(blank)
Sea-level	102	0	(blank)
Levels at a specified height AGL	105	Height, in meters, of the level above ground	(blank)
Fields given as layers	112	Starting level for the layer	Ending level for the layer

When layer fields (Level Type 112) are specified, the starting and ending points for the layer have units that are dependent on the field itself; appropriate values may be found with the g1print.exe and g2print.exe utility programs.

The second group of fields in a Vtable, those that describe how the data are identified within the metgrid and real programs, fall under the column headings shown below.

```
| metgrid  | metgrid | metgrid                                  |
| Name     |  Units  | Description                              |
+----------+---------+------------------------------------------+
```

The most important of these three fields is the "metgrid Name" field, which determines the variable name that will be assigned to a meteorological field when it is written to the intermediate files by ungrib. This name should also match an entry in the METGRID.TBL file, so that the metgrid program can determine how the field is to be horizontally interpolated. The "metgrid Units" and "metgrid Description" fields specify the units and a short description for the field, respectively; here, it is important to note that if no description is given for a field, then *ungrib will not write that field out to the intermediate files*.

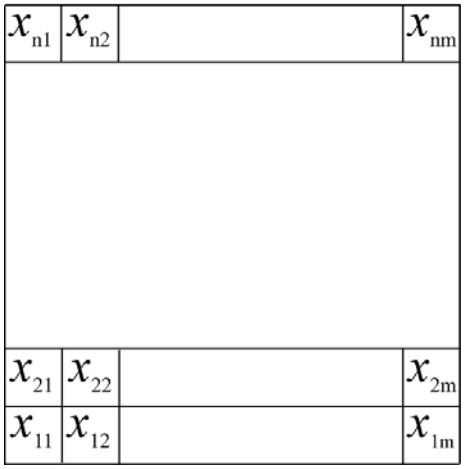
The final group of fields, which provide GRIB2-specific information, are found under the column headings below.

GRIB2 Discp	GRIB2 Catgy	GRIB2 Param	GRIB2 Level

The GRIB2 fields are only needed in a Vtable that is to be used for GRIB Edition 2 data sets, although having these fields in a Vtable does not prevent that Vtable from also being used for GRIB Edition 1 data. For example, the Vtable.GFS file contains GRIB2 Vtable fields, but is used for both 1-degree (GRIB1) GFS and 0.5-degree (GRIB2) GFS data sets. Since Vtables are provided for most known GRIB Edition 2 data sets, the corresponding Vtable fields are not described here at present.

Writing Static Data to the Geogrid Binary Format

The static geographical data sets that are interpolated by the geogrid program are stored as regular 2-d and 3-d arrays written in a simple binary raster format. Users with a new source for a given static field can ingest their data with WPS by writing the data set into this binary format. The geogrid format is capable of supporting single-level and multi-level continuous fields, categorical fields represented as dominant categories, and categorical fields given as fractional fields for each category. The most simple of these field types in terms of representation in the binary format is a categorical field given as a dominant category at each source grid point, an example of which is the 30-second USGS land use data set.



For a categorical field given as dominant categories, the data must first be stored in a regular 2-d array of integers, with each integer giving the dominant category at the corresponding source grid point. Given this array, the data are written to a file, row-by-row, beginning at the bottom, or southern-most, row. For example, in the figure above, the elements of the $n \times m$ array would be written in the order x_{11}, x_{12}, ..., x_{1m}, x_{21}, ..., x_{2m}, ..., x_{n1}, ..., x_{nm}. When written to the file, every element is stored as a 1-, 2-, 3-, or 4-byte integer in big-endian byte order (i.e., for the 4-byte integer *ABCD*, byte *A* is stored at the lowest address and byte *D* at the highest), although little-endian files may be used by setting `endian=little` in the "index" file for the data set. Every element in a file must use the same number of bytes for its storage, and, of course, it is advantageous to use the fewest number of bytes needed to represent the complete range of values in the array.

When writing the binary data to a file, no header, record marker, or additional bytes should be written. For example, a 2-byte 1000×1000 array should result in a file whose size is exactly 2,000,000 bytes. Since Fortran unformatted writes add record markers, *it is not possible to write a geogrid binary-formatted file directly from Fortran*; instead, it is recommended that the C routines in read_geogrid.c and write_geogrid.c (in the geogrid/src directory) be called when writing data, either from C or Fortran code.

Similar in format to a field of dominant categories is the case of a field of continuous, or real, values. Like dominant-category fields, single-level continuous fields are first organized as a regular 2-d array, then written, row-by-row, to a binary file. However, because a continuous field may contain non-integral or negative values, the storage representation of each element within the file is slightly more complex. All elements in the array must first be converted to integral values. This is done by first scaling all elements by a constant, chosen to maintain the required precision, and then removing any remaining fractional part through rounding. For example, if three decimal places of precision are required, the value -2.71828 would need to be divided by 0.001 and rounded to -2718. Following conversion of all array elements to integral values, if any negative values are found in the array, a second conversion must be applied: if elements are stored using 1 byte each, then 2^8 is added to each negative element; for storage using 2 bytes, 2^{16} is added to each negative element; for storage using 3 bytes, 2^{24} is added to each negative element; and for storage using 4 bytes, a value of 2^{32} is added to each

negative element. It is important to note that no conversion is applied to positive elements. Finally, the resulting positive, integral array is written as in the case of a dominant-category field.

Multi-level continuous fields are handled much the same as single-level continuous fields. For an $n \times m \times r$ array, conversion to a positive, integral field is first performed as described above. Then, each $n \times m$ sub-array is written contiguously to the binary file as before, beginning with the smallest r-index. Categorical fields that are given as fractional fields for each possible category can be thought of as multi-level continuous fields, where each level k, $1 \leq k \leq r$, is the fractional field for category k.

When writing a field to a file in the geogrid binary format, the user should adhere to the naming convention used by the geogrid program, which expects data files to have names of the form *xstart-xend.ystart-yend*, where *xstart*, *xend*, *ystart*, and *yend* are five-digit positive integers specifying, respectively, the starting x-index of the array contained in the file, the ending x-index of the array, the starting y-index of the array, and the ending y-index of the array; here, indexing begins at 1, rather than 0. So, for example, an 800 × 1200 array (i.e., 800 rows and 1200 columns) might be named 00001-01200.00001-00800.

When a data set is given in several pieces, each of the pieces may be formed as a regular rectangular array, and each array may be written to a separate file. In this case, the relative locations of the arrays are determined by the range of x- and y-indices in the file names for each of the arrays. It is important to note, however, that *every tile in a data set must have the same* x- *and* y-*dimensions*, and that tiles of data within a data set must not overlap; furthermore, all tiles must start and end on multiples of the index ranges. For example, the global 30-second USGS topography data set is divided into arrays of dimension 1200 × 1200, with each array containing a 10-degree × 10-degree piece of the data set; the file whose south-west corner is located at (90S, 180W) is named 00001-01200.00001-01200, and the file whose north-east corner is located at (90N, 180E) is named 42001-43200.20401-21600.

If a data set is to be split into multiple tiles, and the number of grid points in, say, the x-direction is not evenly divided by the number of tiles in the x-direction, then the last column of tiles must be padded with a flag value (specified in the index file using the `missing_value` keyword) so that all tiles have the same dimensions. For example, if a data set has 2456 points in the x-direction, and three tiles in the x-direction will be used, the range of x-coordinates of the tiles might be 1 – 820, 821 – 1640, and 1641 – 2460, with columns 2457 through 2460 being filled with a flag value.

Clearly, since the starting and ending indices must have five digits, a field cannot have more than 99999 data points in either of the x- or y-directions. In case a field has more than 99999 data points in either dimension, the user can simply split the data set into several smaller data sets which will be identified separately to geogrid. For example, a very large global data set may be split into data sets for the Eastern and Western hemispheres.

Besides the binary data files, geogrid requires one extra metadata file per data set. This metadata file is always named 'index', and thus, two data sets cannot reside in the same directory. Essentially, this metadata file is the first file that geogrid looks for when processing a data set, and the contents of the file provide geogrid with all of the information necessary for constructing names of possible data files. The contents of an example index file are given below.

```
type = continuous
signed = yes
projection = regular_ll
dx = 0.00833333
dy = 0.00833333
known_x = 1.0
known_y = 1.0
known_lat = -89.99583
known_lon = -179.99583
wordsize = 2
tile_x = 1200
tile_y = 1200
tile_z = 1
tile_bdr=3
units="meters MSL"
description="Topography height"
```

For a complete listing of keywords that may appear in an index file, along with the meaning of each keyword, the user is referred to the section on index file options.

Description of the Namelist Variables

A. SHARE section

This section describes variables that are used by more than one WPS program. For example, the `wrf_core` variable specifies whether the WPS is to produce data for the ARW or the NMM core – information which is needed by both the geogrid and metgrid programs.

1. WRF_CORE : A character string set to either `'ARW'` or `'NMM'` that tells the WPS which dynamical core the input data are being prepared for. Default value is `'ARW'`.

2. MAX_DOM : An integer specifying the total number of domains/nests, including the parent domain, in the simulation. Default value is 1.

3. START_YEAR : A list of MAX_DOM 4-digit integers specifying the starting UTC year of the simulation for each nest. No default value.

4. START_MONTH : A list of MAX_DOM 2-digit integers specifying the starting UTC month of the simulation for each nest. No default value.

5. START_DAY : A list of MAX_DOM 2-digit integers specifying the starting UTC day of the simulation for each nest. No default value.

6. START_HOUR : A list of MAX_DOM 2-digit integers specifying the starting UTC hour of the simulation for each nest. No default value.

7. END_YEAR : A list of MAX_DOM 4-digit integers specifying the ending UTC year of the simulation for each nest. No default value.

8. END_MONTH : A list of MAX_DOM 2-digit integers specifying the ending UTC month of the simulation for each nest. No default value.

9. END_DAY : A list of MAX_DOM 2-digit integers specifying the ending UTC day of the simulation for each nest. No default value.

10. END_HOUR : A list of MAX_DOM 2-digit integers specifying the ending UTC hour of the simulation for each nest. No default value.

11. START_DATE : A list of MAX_DOM character strings of the form `'YYYY-MM-DD_HH:mm:ss'` specifying the starting UTC date of the simulation for each nest. The `start_date` variable is an alternate to specifying `start_year`, `start_month`, `start_day`, and `start_hour`, and if both methods are used for specifying the starting time, the `start_date` variable will take precedence. No default value.

12. END_DATE : A list of MAX_DOM character strings of the form `'YYYY-MM-DD_HH:mm:ss'` specifying the ending UTC date of the simulation for each nest. The `end_date` variable is an alternate to specifying `end_year`, `end_month`, `end_day`, and `end_hour`, and if both methods are used for specifying the ending time, the `end_date` variable will take precedence. No default value.

13. INTERVAL_SECONDS : The integer number of seconds between time-varying meteorological input files. No default value.

14. ACTIVE_GRID : A list of MAX_DOM logical values specifying, for each grid, whether that grid should be processed by geogrid and metgrid. Default value is `.TRUE.`.

15. IO_FORM_GEOGRID : The WRF I/O API format that the domain files created by the geogrid program will be written in. Possible options are: 1 for binary; 2 for NetCDF; 3 for GRIB1. When option 1 is given, domain files will have a suffix of .int; when option 2 is given, domain files will have a suffix of .nc; when option 3 is given, domain files will have a suffix of .gr1. Default value is 2 (NetCDF).

16. OPT_OUTPUT_FROM_GEOGRID_PATH : A character string giving the path, either relative or absolute, to the location where output files from geogrid should be written to and read from. Default value is `'./'`.

17. DEBUG_LEVEL : An integer value indicating the extent to which different types of messages should be sent to standard output. When `debug_level` is set to 0, only generally useful messages and warning messages will be written to standard output. When `debug_level` is greater than 100, informational messages that provide further runtime details are also written to standard output. Debugging messages and messages specifically intended for log files are never written to standard output, but are always written to the log files. Default value is 0.

B. GEOGRID section

This section specifies variables that are specific to the geogrid program. Variables in the geogrid section primarily define the size and location of all model domains, and where the static geographical data are found.

1. PARENT_ID : A list of MAX_DOM integers specifying, for each nest, the domain number of the nest's parent; for the coarsest domain, this variable should be set to 1. Default value is 1.

2. PARENT_GRID_RATIO : A list of MAX_DOM integers specifying, for each nest, the nesting ratio relative to the domain's parent. No default value.

3. I_PARENT_START : A list of MAX_DOM integers specifying, for each nest, the x-coordinate of the lower-left corner of the nest in the parent *unstaggered* grid. For the coarsest domain, a value of 1 should be specified. No default value.

4. J_PARENT_START : A list of MAX_DOM integers specifying, for each nest, the y-coordinate of the lower-left corner of the nest in the parent *unstaggered* grid. For the coarsest domain, a value of 1 should be specified. No default value.

5. S_WE : A list of MAX_DOM integers which should all be set to 1. Default value is 1.

6. E_WE : A list of MAX_DOM integers specifying, for each nest, the nest's full west-east dimension. For nested domains, `e_we` must be one greater than an integer multiple of the nest's `parent_grid_ratio` (i.e., `e_ew` = *n**`parent_grid_ratio`+1 for some positive integer *n*). No default value.

7. S_SN : A list of MAX_DOM integers which should all be set to 1. Default value is 1.

8. E_SN : A list of MAX_DOM integers specifying, for each nest, the nest's full south-north dimension. For nested domains, `e_sn` must be one greater than an integer multiple of the nest's `parent_grid_ratio` (i.e., `e_sn` = *n**`parent_grid_ratio`+1 for some positive integer *n*). No default value.

9. GEOG_DATA_RES : A list of MAX_DOM character strings specifying, for each nest, a corresponding resolution or list of resolutions separated by + symbols of source data to be used when interpolating static terrestrial data to the nest's grid. For each nest, this string should contain a resolution matching a string preceding a colon in a `rel_path` or `abs_path` specification (see the description of GEOGRID.TBL options) in the GEOGRID.TBL file for each field. If a resolution in the string does not match any such string in a `rel_path` or `abs_path` specification for a field in GEOGRID.TBL, a default resolution of data for that field, if one is specified, will be used. If multiple resolutions match, the first resolution to match a string in a `rel_path` or `abs_path` specification in the GEOGRID.TBL file will be used. Default value is `'default'`.

10. DX : A real value specifying the grid distance in the x-direction where the map scale factor is 1. For ARW, the grid distance is in meters for the `'polar'`, `'lambert'`, and `'mercator'` projection, and in degrees longitude for the `'lat-lon'` projection; for NMM, the grid distance is in degrees longitude. Grid distances for nests are determined recursively based on values specified for `parent_grid_ratio` and `parent_id`. No default value.

11. DY : A real value specifying the nominal grid distance in the y-direction where the map scale factor is 1. For ARW, the grid distance is in meters for the `'polar'`, `'lambert'`, and `'mercator'` projection, and in degrees latitude for the `'lat-lon'` projection; for NMM, the grid distance is in degrees latitude. Grid distances for nests are determined recursively based on values specified for `parent_grid_ratio` and `parent_id`. No default value.

12. MAP_PROJ : A character string specifying the projection of the simulation domain. For ARW, accepted projections are `'lambert'`, `'polar'`, `'mercator'`, and `'lat-lon'`; for NMM, a projection of `'rotated_ll'` must be specified. Default value is `'lambert'`.

13. REF_LAT : A real value specifying the latitude part of a (latitude, longitude) location whose (i,j) location in the simulation domain is known. For ARW, `ref_lat` gives the latitude of the center-point of the coarse domain by default (i.e., when `ref_x` and `ref_y` are not specified). For NMM, `ref_lat` always gives the latitude to which the origin is rotated. No default value.

14. REF_LON : A real value specifying the longitude part of a (latitude, longitude) location whose (i, j) location in the simulation domain is known. For ARW, `ref_lon` gives the longitude of the center-point of the coarse domain by default (i.e., when `ref_x` and `ref_y` are not specified). For NMM, `ref_lon` always gives the longitude to which the origin is rotated. For both ARW and NMM, west longitudes are negative, and the value of `ref_lon` should be in the range [-180, 180]. No default value.

15. REF_X : A real value specifying the i part of an (i, j) location whose (latitude, longitude) location in the simulation domain is known. The (i, j) location is always given with respect to the mass-staggered grid, whose dimensions are one less than the dimensions of the unstaggered grid. Default value is (((`E_WE`-1.)+1.)/2.) = (`E_WE`/2.).

16. REF_Y : A real value specifying the j part of an (i, j) location whose (latitude, longitude) location in the simulation domain is known. The (i, j) location is always given with respect to the mass-staggered grid, whose dimensions are one less than the dimensions of the unstaggered grid. Default value is (((`E_SN`-1.)+1.)/2.) = (`E_SN`/2.).

17. TRUELAT1 : A real value specifying, for ARW, the first true latitude for the Lambert conformal projection, or the only true latitude for the Mercator and polar stereographic projections. For NMM, `truelat1` is ignored. No default value.

18. TRUELAT2 : A real value specifying, for ARW, the second true latitude for the Lambert conformal conic projection. For all other projections, `truelat2` is ignored. No default value.

19. STAND_LON : A real value specifying, for ARW, the longitude that is parallel with the y-axis in the Lambert conformal and polar stereographic projections. For the regular latitude-longitude projection, this value gives the rotation about the earth's geographic poles. For NMM, `stand_lon` is ignored. No default value.

20. POLE_LAT : For the latitude-longitude projection for ARW, the latitude of the North Pole with respect to the computational latitude-longitude grid in which -90.0° latitude is at the bottom of a global domain, 90.0° latitude is at the top, and 180.0° longitude is at the center. Default value is 90.0.

21. POLE_LON : For the latitude-longitude projection for ARW, the longitude of the North Pole with respect to the computational lat/lon grid in which -90.0° latitude is at the bottom of a global domain, 90.0° latitude is at the top, and 180.0° longitude is at the center. Default value is 0.0.

22. GEOG_DATA_PATH : A character string giving the path, either relative or absolute, to the directory where the geographical data directories may be found. This path is the one to which `rel_path` specifications in the GEOGRID.TBL file are given in relation to. No default value.

23. OPT_GEOGRID_TBL_PATH : A character string giving the path, either relative or absolute, to the GEOGRID.TBL file. The path should not contain the actual file name, as GEOGRID.TBL is assumed, but should only give the path where this file is located. Default value is `'./geogrid/'`.

C. UNGRIB section

Currently, this section contains only two variables, which determine the output format written by ungrib and the name of the output files.

1. OUT_FORMAT : A character string set either to `'WPS'`, `'SI'`, or `'MM5'`. If set to

'MM5', ungrib will write output in the format of the MM5 pregrid program; if set to 'SI', ungrib will write output in the format of grib_prep.exe; if set to 'WPS', ungrib will write data in the WPS intermediate format. Default value is 'WPS'.

2. PREFIX : A character string that will be used as the prefix for intermediate-format files created by ungrib; here, prefix refers to the string *PREFIX* in the filename *PREFIX*:*YYYY-MM-DD_HH* of an intermediate file. The prefix may contain path information, either relative or absolute, in which case the intermediate files will be written in the directory specified. This option may be useful to avoid renaming intermediate files if ungrib is to be run on multiple sources of GRIB data. Default value is 'FILE'.

D. METGRID section

This section defines variables used only by the metgrid program. Typically, the user will be interested in the fg_name variable, and may need to modify other variables of this section less frequently.

1. FG_NAME : A list of character strings specifying the path and prefix of ungribbed data files. The path may be relative or absolute, and the prefix should contain all characters of the filenames up to, but not including, the colon preceding the date. When more than one fg_name is specified, and the same field is found in two or more input sources, the data in the last encountered source will take priority over all preceding sources for that field. Default value is an empty list (i.e., no meteorological fields).

2. CONSTANTS_NAME : A list of character strings specifying the path and full filename of ungribbed data files which are time-invariant. The path may be relative or absolute, and the filename should be the complete filename; since the data are assumed to be time-invariant, no date will be appended to the specified filename. Default value is an empty list (i.e., no constant fields).

3. IO_FORM_METGRID : The WRF I/O API format that the output created by the metgrid program will be written in. Possible options are: 1 for binary; 2 for NetCDF; 3 for GRIB1. When option 1 is given, output files will have a suffix of .int; when option 2 is given, output files will have a suffix of .nc; when option 3 is given, output files will have a suffix of .gr1. Default value is 2 (NetCDF).

4. OPT_OUTPUT_FROM_METGRID_PATH : A character string giving the path, either relative or absolute, to the location where output files from metgrid should be written to. The default value is the current working directory (i.e., the default value is './').

5. OPT_METGRID_TBL_PATH : A character string giving the path, either relative or absolute, to the METGRID.TBL file; the path should not contain the actual file name, as METGRID.TBL is assumed, but should only give the path where this file is located. Default value is './metgrid/'.

6. OPT_IGNORE_DOM_CENTER : A logical value, either `.TRUE.` or `.FALSE.`, specifying whether, for times other than the initial time, interpolation of meteorological fields to points on the interior of the simulation domain should be avoided in order to decrease the runtime of metgrid. This option currently has no effect. Default value is `.FALSE.`.

Description of GEOGRID.TBL Options

The GEOGRID.TBL file is a text file that defines parameters of each of the data sets to be interpolated by geogrid. Each data set is defined in a separate section, with sections being delimited by a line of equality symbols (e.g., '==========='). Within each section, there are specifications, each of which has the form of *keyword=value*. Some keywords are required in each data set section, while others are optional; some keywords are mutually exclusive with other keywords. Below, the possible keywords and their expected range of values are described.

1. NAME : A character string specifying the name that will be assigned to the interpolated field upon output. No default value.

2. PRIORITY : An integer specifying the priority that the data source identified in the table section takes with respect to other sources of data for the same field. If a field has *n* sources of data, then there must be *n* separate table entries for the field, each of which must be given a unique value for `priority` in the range [1, *n*]. No default value.

3. DEST_TYPE : A character string, either `categorical` or `continuous`, that tells whether the interpolated field from the data source given in the table section is to be treated as a continuous or a categorical field. No default value.

4. INTERP_OPTION : A sequence of one or more character strings, which are the names of interpolation methods to be used when horizontally interpolating the field. Available interpolation methods are: `average_4pt`, `average_16pt`, `wt_average_4pt`, `wt_average_16pt`, `nearest_neighbor`, `four_pt`, `sixteen_pt`, `search`, `average_gcell(`*r*`)` ; for the grid cell average method (`average_gcell`), the optional argument *r* specifies the minimum ratio of source data resolution to simulation grid resolution at which the method will be applied; unless specified, *r* = 0.0, and the option is used for any ratio. When a sequence of two or more methods are given, the methods should be separated by a `+` sign. No default value.

5. SMOOTH_OPTION : A character string giving the name of a smoothing method to be applied to the field after interpolation. Available smoothing options are: `1-2-1`, `smth-desmth`, and `smth-desmth_special` (ARW only). Default value is null (i.e., no smoothing is applied).

6. SMOOTH_PASSES : If smoothing is to be performed on the interpolated field, `smooth_passes` specifies an integer number of passes of the smoothing method to apply to the field. Default value is 1.

7. REL_PATH : A character string specifying the path relative to the path given in the namelist variable `geog_data_path`. A specification is of the general form *RES_STRING*:*REL_PATH*, where *RES_STRING* is a character string identifying the source or resolution of the data in some unique way and may be specified in the namelist variable `geog_data_res`, and *REL_PATH* is a path relative to `geog_data_path` where the index and data tiles for the data source are found. More than one `rel_path` specification may be given in a table section if there are multiple sources or resolutions for the data source, just as multiple resolutions may be specified (in a sequence delimited by `+` symbols) for `geog_data_res`. See also `abs_path`. No default value.

8. ABS_PATH : A character string specifying the absolute path to the index and data tiles for the data source. A specification is of the general form *RES_STRING*:*ABS_PATH*, where *RES_STRING* is a character string identifying the source or resolution of the data in some unique way and may be specified in the namelist variable `geog_data_res`, and *ABS_PATH* is the absolute path to the data source's files. More than one `abs_path` specification may be given in a table section if there are multiple sources or resolutions for the data source, just as multiple resolutions may be specified (in a sequence delimited by `+` symbols) for `geog_data_res`. See also `rel_path`. No default value.

9. OUTPUT_STAGGER : A character string specifying the grid staggering to which the field is to be interpolated. For ARW domains, possible values are `U`, `V`, and `M`; for NMM domains, possible values are `HH` and `VV`. Default value for ARW is `M`; default value for NMM is `HH`.

10. LANDMASK_WATER : One or more comma-separated integer values giving the indices of the categories within the field that represents water. When `landmask_water` is specified in the table section of a field for which `dest_type=categorical`, the LANDMASK field will be computed from the field using the specified categories as the water categories. The keywords `landmask_water` and `landmask_land` are mutually exclusive. Default value is null (i.e., a landmask will not be computed from the field).

11. LANDMASK_LAND : One or more comma-separated integer values giving the indices of the categories within the field that represents land. When `landmask_water` is specified in the table section of a field for which `dest_type=categorical`, the LANDMASK field will be computed from the field using the specified categories as the land categories. The keywords `landmask_water` and `landmask_land` are mutually exclusive. Default value is null (i.e., a landmask will not be computed from the field).

12. MASKED : Either `land` or `water`, indicating that the field is not valid at land or water points, respectively. If the `masked` keyword is used for a field, those grid points that are of the masked type (land or water) will be assigned the value specified by `fill_missing`. Default value is null (i.e., the field is not masked).

13. FILL_MISSING : A real value used to fill in any missing or masked grid points in the interpolated field. Default value is 1.E20.

14. HALT_ON_MISSING : Either `yes` or `no`, indicating whether geogrid should halt with a fatal message when a missing value is encountered in the interpolated field. Default value is `no`.

15. DOMINANT_CATEGORY : When specified as a character string, the effect is to cause geogrid to compute the dominant category from the fractional categorical field, and to output the dominant category field with the name specified by the value of `dominant_category`. This option can only be used for fields with `dest_type=categorical`. Default value is null (i.e., no dominant category will be computed from the fractional categorical field).

16. DOMINANT_ONLY : When specified as a character string, the effect is similar to that of the `dominant_category` keyword: geogrid will compute the dominant category from the fractional categorical field and output the dominant category field with the name specified by the value of `dominant_only`. Unlike with `dominant_category`, though, when `dominant_only` is used, the fractional categorical field will not appear in the geogrid output. This option can only be used for fields with `dest_type=categorical`. Default value is null (i.e., no dominant category will be computed from the fractional categorical field).

17. DF_DX : When `df_dx` is assigned a character string value, the effect is to cause geogrid to compute the directional derivative of the field in the x-direction using a central difference along the interior of the domain, or a one-sided difference at the boundary of the domain; the derivative field will be named according to the character string assigned to the keyword `df_dx`. Default value is null (i.e., no derivative field is computed).

18. DF_DY : When `df_dy` is assigned a character string value, the effect is to cause geogrid to compute the directional derivative of the field in the y-direction using a central difference along the interior of the domain, or a one-sided difference at the boundary of the domain; the derivative field will be named according to the character string assigned to the keyword `df_dy`. Default value is null (i.e., no derivative field is computed).

19. Z_DIM_NAME : For 3-dimensional output fields, a character string giving the name of the vertical dimension, or z-dimension. A continuous field may have multiple levels, and thus be a 3-dimensional field, and a categorical field may take the form of a 3-dimensional field if it is written out as fractional fields for each category. No default value.

Description of index Options

Related to the GEOGRID.TBL are the index files that are associated with each static data set. An index file defines parameters specific to that data set, while the GEOGRID.TBL file describes how each of the data sets should be treated by geogrid. As with the GEOGRID.TBL file, specifications in an index file are of the form *keyword=value*. Below are possible keywords and their possible values.

1. PROJECTION : A character string specifying the projection of the data, which may be either `lambert`, `polar`, `mercator`, `regular_ll`, `albers_nad83`, or `polar_wgs84`. No default value.

2. TYPE : A character string, either `categorical` or `continuous`, that determines whether the data in the data files should be interpreted as a continuous field or as discrete indices. For categorical data represented by a fractional field for each possible category, `type` should be set to `continuous`. No default value.

3. SIGNED : Either `yes` or `no`, indicating whether the values in the data files (which are always represented as integers) are signed in two's complement form or not. Default value is `no`.

4. UNITS : A character string, enclosed in quotation marks ("), specifying the units of the interpolated field; the string will be written to the geogrid output files as a variable time-independent attribute. No default value.

5. DESCRIPTION : A character string, enclosed in quotation marks ("), giving a short description of the interpolated field; the string will be written to the geogrid output files as a variable time-independent attribute. No default value.

6. DX : A real value giving the grid spacing in the x-direction of the data set. If `projection` is one of `lambert`, `polar`, `mercator`, `albers_nad83`, or `polar_wgs84`, `dx` gives the grid spacing in meters; if `projection` is `regular_ll`, `dx` gives the grid spacing in degrees. No default value.

7. DY : A real value giving the grid spacing in the y-direction of the data set. If `projection` is one of `lambert`, `polar`, `mercator`, `albers_nad83`, or `polar_wgs84`, `dy` gives the grid spacing in meters; if `projection` is `regular_ll`, `dy` gives the grid spacing in degrees. No default value.

8. KNOWN_X : A real value specifying the i-coordinate of an (i,j) location corresponding to a (latitude, longitude) location that is known in the projection. Default value is 1.

9. KNOWN_Y : A real value specifying the j-coordinate of an (i,j) location corresponding to a (latitude, longitude) location that is known in the projection. Default value is 1.

10. KNOWN_LAT : A real value specifying the latitude of a (latitude, longitude) location that is known in the projection. No default value.

11. KNOWN_LON : A real value specifying the longitude of a (latitude, longitude) location that is known in the projection. No default value.

12. STDLON : A real value specifying the longitude that is parallel with the y-axis in conic and azimuthal projections. No default value.

13. TRUELAT1 : A real value specifying the first true latitude for conic projections or the only true latitude for azimuthal projections. No default value.

14. TRUELAT2 : A real value specifying the second true latitude for conic projections. No default value.

15. WORDSIZE : An integer giving the number of bytes used to represent the value of each grid point in the data files. No default value.

16. TILE_X : An integer specifying the number of grid points in the x-direction, *excluding any halo points*, for a single tile of source data. No default value.

17. TILE_Y : An integer specifying the number of grid points in the y-direction, *excluding any halo points*, for a single tile of source data. No default value.

18. TILE_Z : An integer specifying the number of grid points in the z-direction for a single tile of source data; this keyword serves as an alternative to the pair of keywords `tile_z_start` and `tile_z_end`, and when this keyword is used, the starting z-index is assumed to be 1. No default value.

19. TILE_Z_START : An integer specifying the starting index in the z-direction of the array in the data files. If this keyword is used, `tile_z_end` must also be specified. No default value.

20. TILE_Z_END : An integer specifying the ending index in the z-direction of the array in the data files. If this keyword is used, `tile_z_start` must also be specified. No default value

21. CATEGORY_MIN : For categorical data (`type=categorical`), an integer specifying the minimum category index that is found in the data set. If this keyword is used, `category_max` must also be specified. No default value.

22. CATEGORY_MAX : For categorical data (`type=categorical`), an integer specifying the maximum category index that is found in the data set. If this keyword is used, `category_min` must also be specified. No default value.

23. TILE_BDR : An integer specifying the halo width, in grid points, for each tile of data. Default value is 0.

24. MISSING_VALUE : A real value that, when encountered in the data set, should be interpreted as missing data. No default value.

25. SCALE_FACTOR : A real value that data should be scaled by (through multiplication) after being read in as integers from tiles of the data set. Default value is 1.

26. ROW_ORDER : A character string, either `bottom_top` or `top_bottom`, specifying whether the rows of the data set arrays were written proceeding from the lowest-index row to the highest (`bottom_top`) or from highest to lowest (`top_bottom`). This keyword may be useful when utilizing some USGS data sets, which are provided in `top_bottom` order. Default value is `bottom_top`.

27. ENDIAN : A character string, either `big` or `little`, specifying whether the values in the static data set arrays are in big-endian or little-endian byte order. Default value is `big`.

28. ISWATER : An integer specifying the land use category of water. Default value is 16.

29. ISLAKE : An integer specifying the land use category of inland water bodies. Default value is -1 (i.e., no separate inland water category).

30. ISICE : An integer specifying the land use category of ice. Default value is 24.

31. ISURBAN : An integer specifying the land use category of urban areas. Default value is 1.

32. ISOILWATER : An integer specifying the soil category of water. Default value is 14.

33. MMINLU : A character string, enclosed in quotation marks ("), indicating which section of WRF's LANDUSE.TBL and VEGPARM.TBL will be used when looking up parameters for land use categories. Default value is `"USGS"`.

Description of METGRID.TBL Options

The METGRID.TBL file is a text file that defines parameters of each of the meteorological fields to be interpolated by metgrid. Parameters for each field are defined in a separate section, with sections being delimited by a line of equality symbols (e.g., '==========='). Within each section, there are specifications, each of which has the form of *keyword=value*. Some keywords are required in a section, while others are optional; some keywords are mutually exclusive with other keywords. Below, the possible keywords and their expected range of values are described.

1. NAME : A character string giving the name of the meteorological field to which the containing section of the table pertains. The name should exactly match that of the field as given in the intermediate files (and, thus, the name given in the Vtable used in generating the intermediate files). This field is required. No default value.

2. OUTPUT : Either `yes` or `no`, indicating whether the field is to be written to the metgrid output files or not. Default value is `yes`.

3. MANDATORY : Either `yes` or `no`, indicating whether the field is required for successful completion of metgrid. Default value is `no`.

4. OUTPUT_NAME : A character string giving the name that the interpolated field should be output as. When a value is specified for `output_name`, the interpolation options from the table section pertaining to the field with the specified name are used. Thus, the effects of specifying `output_name` are two-fold: The interpolated field is assigned the specified name before being written out, and the interpolation methods are taken from the section pertaining to the field whose name matches the value assigned to the `output_name` keyword. No default value.

5. FROM_INPUT : A character string used to compare against the values in the `fg_name` namelist variable; if `from_input` is specified, the containing table section will only be used when the time-varying input source has a filename that contains the value of `from_input` as a substring. Thus, `from_input` may be used to specify different interpolation options for the same field, depending on which source of the field is being processed. No default value.

6. OUTPUT_STAGGER : The model grid staggering to which the field should be interpolated. For ARW, this must be one of `U`, `V`, and `M`; for NMM, this must be one of `HH` and `VV`. Default value for ARW is `M`; default value for NMM is `HH`.

7. IS_U_FIELD : Either `yes` or `no`, indicating whether the field is to be used as the wind U-component field. For ARW, the wind U-component field must be interpolated to the U staggering (`output_stagger=U`); for NMM, the wind U-component field must be interpolated to the V staggering (`output_stagger=VV`). Default value is `no`.

8. IS_V_FIELD : Either `yes` or `no`, indicating whether the field is to be used as the wind V-component field. For ARW, the wind V-component field must be interpolated to the V staggering (`output_stagger=V`); for NMM, the wind V-component field must be interpolated to the V staggering (`output_stagger=VV`). Default value is `no`.

9. INTERP_OPTION : A sequence of one or more names of interpolation methods to be used when horizontally interpolating the field. Available interpolation methods are: `average_4pt`, `average_16pt`, `wt_average_4pt`, `wt_average_16pt`, `nearest_neighbor`, `four_pt`, `sixteen_pt`, `search`, `average_gcell(`*r*`)` ; for the grid cell average method (`average_gcell`), the optional argument *r* specifies the minimum ratio of source data resolution to simulation grid resolution at which the method will be

applied; unless specified, $r = 0.0$, and the option is used for any ratio. When a sequence of two or more methods are given, the methods should be separated by a + sign. Default value is `nearest_neighbor`.

10. INTERP_MASK : The name of the field to be used as an interpolation mask, along with the value within that field which signals masked points. A specification takes the form *field*(*maskval*), where *field* is the name of the field and *maskval* is a real value. Default value is no mask.

11. INTERP_LAND_MASK : The name of the field to be used as an interpolation mask when interpolating to water points (determined by the static LANDMASK field), along with the value within that field which signals land points. A specification takes the form *field*(*maskval*), where *field* is the name of the field and *maskval* is a real value. Default value is no mask.

12. INTERP_WATER_MASK : The name of the field to be used as an interpolation mask when interpolating to land points (determined by the static LANDMASK field), along with the value within that field which signals water points. A specification takes the form *field*(*maskval*), where *field* is the name of the field and *maskval* is a real value. Default value is no mask.

13. FILL_MISSING : A real number specifying the value to be assigned to model grid points that received no interpolated value, for example, because of missing or incomplete meteorological data. Default value is 1.E20.

14. Z_DIM_NAME : For 3-dimensional meteorological fields, a character string giving the name of the vertical dimension to be used for the field on output. Default value is `num_metgrid_levels`.

15. DERIVED : Either `yes` or `no`, indicating whether the field is to be derived from other interpolated fields, rather than interpolated from an input field. Default value is `no`.

16. FILL_LEV : The `fill_lev` keyword, which may be specified multiple times within a table section, specifies how a level of the field should be filled if that level does not already exist. A generic value for the keyword takes the form *DLEVEL*:*FIELD*(*SLEVEL*), where *DLEVEL* specifies the level in the field to be filled, *FIELD* specifies the source field from which to copy levels, and *SLEVEL* specifies the level within the source field to use. *DLEVEL* may either be an integer or the string `all`. *FIELD* may either be the name of another field, the string `const`, or the string `vertical_index`. If *FIELD* is specified as `const`, then *SLEVEL* is a constant value that will be used to fill with; if *FIELD* is specified as `vertical_index`, then (*SLEVEL*) must not be specified, and the value of the vertical index of the source field is used; if *DLEVEL* is 'all', then all levels from the field specified by the `level_template` keyword are used to fill the corresponding levels in the field, one at a time. No default value.

17. LEVEL_TEMPLATE : A character string giving the name of a field from which a list of vertical levels should be obtained and used as a template. This keyword is used in conjunction with a `fill_lev` specification that uses `all` in the *DLEVEL* part of its specification. No default value.

18. MASKED : Either `land` or `water`, indicating whether the field is invalid over land or water, respectively. When a field is masked, or invalid, the static LANDMASK field will be used to determine which model grid points the field should be interpolated to; invalid points will be assigned the value given by the `FILL_MISSING` keyword. Default value is null (i.e., the field is valid for both land and water points).

19. MISSING_VALUE : A real number giving the value in the input field that is assumed to represent missing data. No default value.

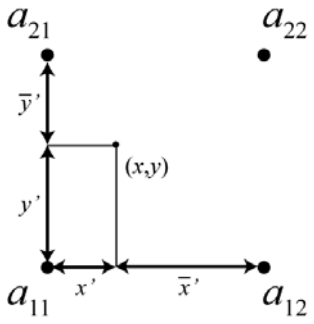
20. VERTICAL_INTERP_OPTION : A character string specifying the vertical interpolation method that should be used when vertically interpolating to missing points. Currently, this option is not implemented. No default value.

21. FLAG_IN_OUTPUT : A character string giving the name of a global attribute which will be assigned a value of 1 and written to the metgrid output if the interpolated field is to be output (output=yes). Default value is null (i.e., no flag will be written for the field).

Available Interpolation Options in Geogrid and Metgrid

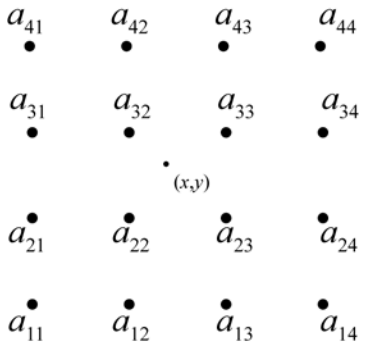
Through the GEOGRID.TBL and METGRID.TBL files, the user can control the method by which source data – either static fields in the case of geogrid or meteorological fields in the case of metgrid – are interpolated. In fact, a list of interpolation methods may be given, in which case, if it is not possible to employ the *i*-th method in the list, the (*i*+1)-st method will be employed, until either some method can be used or there are no methods left to try in the list. For example, to use a four-point bi-linear interpolation scheme for a field, we could specify `interp_option=four_pt`. However, if the field had areas of missing values, which could prevent the `four_pt` option from being used, we could request that a simple four-point average be tried if the `four_pt` method couldn't be used by specifying `interp_option=four_pt+average_4pt` instead. Below, each of the available interpolation options in the WPS are described conceptually; for the details of each method, the user is referred to the source code in the file WPS/geogrid/src/interp_options.F.

1. four_pt : Four-point bi-linear interpolation



The four-point bi-linear interpolation method requires four valid source points a_{ij}, $1 \le i, j \le 2$, surrounding the point (x,y), to which geogrid or metgrid must interpolate, as illustrated in the figure above. Intuitively, the method works by linearly interpolating to the x-coordinate of the point (x,y) between a_{11} and a_{12}, and between a_{21} and a_{22}, and then linearly interpolating to the y-coordinate using these two interpolated values.

2. sixteen_pt : Sixteen-point overlapping parabolic interpolation



The sixteen_pt overlapping parabolic interpolation method requires sixteen valid source points surrounding the point (x,y), as illustrated in the figure above. The method works by fitting one parabola to the points a_{i1}, a_{i2}, and a_{i3}, and another parabola to the points a_{i2}, a_{i3}, and a_{i4}, for row i, $1 \le i \le 4$; then, an intermediate interpolated value p_i within row i at the x-coordinate of the point is computed by taking an average of the values of the two parabolas evaluated at x, with the average being weighted linearly by the distance of x from a_{i2} and a_{i3}. Finally, the interpolated value at (x,y) is found by performing the same operations as for a row of points, but for the column of interpolated values p_i to the y-coordinate of (x,y).

3. average_4pt : Simple four-point average interpolation

The four-point average interpolation method requires at least one valid source data point from the four source points surrounding the point (*x*,*y*). The interpolated value is simply the average value of all valid values among these four points.

4. wt_average_4pt : Weighted four-point average interpolation

The weighted four-point average interpolation method can handle missing or masked source data points, and the interpolated value is given as the weighted average of all valid values, with the weight w_{ij} for the source point a_{ij}, $1 \le i, j \le 2$, given by

$$w_{ij} = \max\{0, 1 - \sqrt{(x - x_i)^2 + (y - y_j)^2}\}.$$

Here, x_i is the *x*-coordinate of a_{ij} and y_j is the *y*-coordinate of a_{ij}.

5. average_16pt : Simple sixteen-point average interpolation

The sixteen-point average interpolation method works in an identical way to the four-point average, but considers the sixteen points surrounding the point (*x*,*y*).

6. wt_average_16pt : Weighted sixteen-point average interpolation

The weighted sixteen-point average interpolation method works like the weighted four-point average, but considers the sixteen points surrounding (*x*,*y*); the weights in this method are given by

$$w_{ij} = \max\{0, 2 - \sqrt{(x - x_i)^2 + (y - y_j)^2}\},$$

where x_i and y_j are as defined for the weighted four-point method, and $1 \le i, j \le 4$.

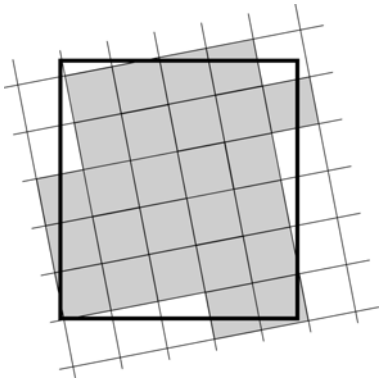
7. nearest_neighbor : Nearest neighbor interpolation

The nearest neighbor interpolation method simply sets the interpolated value at (*x*,*y*) to the value of the nearest source data point, regardless of whether this nearest source point is valid, missing, or masked.

8. search : Breadth-first search interpolation

The breadth-first search option works by treating the source data array as a 2-d grid graph, where each source data point, whether valid or not, is represented by a vertex. Then, the value assigned to the point (x,y) is found by beginning a breadth-first search at the vertex corresponding to the nearest neighbor of (x,y), and stopping once a vertex representing a valid (i.e., not masked or missing) source data point is found. In effect, this method can be thought of as "nearest *valid* neighbor".

9. average_gcell : Model grid-cell average



The grid-cell average interpolator may be used when the resolution of the source data is higher than the resolution of the model grid. For a model grid cell Γ, the method takes a simple average of the values of all source data points that are nearer to the center of Γ than to the center of any other grid cell. The operation of the grid-cell average method is illustrated in the figure above, where the interpolated value for the model grid cell – represented as the large rectangle – is given by the simple average of the values of all of the shaded source grid cells.

Land Use and Soil Categories in the Static Data

The default land use and soil category data sets that are provided as part of the WPS static data tar file contain categories that are matched with the USGS categories described in the VEGPARM.TBL and SOILPARM.TBL files in the WRF run directory. Descriptions of the 24 land use categories and 16 soil categories are provided in the tables below.

Table 1: USGS 24-category Land Use Categories

Land Use Category	Land Use Description
1	Urban and Built-up Land
2	Dryland Cropland and Pasture
3	Irrigated Cropland and Pasture
4	Mixed Dryland/Irrigated Cropland and Pasture
5	Cropland/Grassland Mosaic
6	Cropland/Woodland Mosaic
7	Grassland
8	Shrubland
9	Mixed Shrubland/Grassland
10	Savanna
11	Deciduous Broadleaf Forest
12	Deciduous Needleleaf Forest
13	Evergreen Broadleaf
14	Evergreen Needleleaf
15	Mixed Forest
16	Water Bodies
17	Herbaceous Wetland
18	Wooden Wetland
19	Barren or Sparsely Vegetated
20	Herbaceous Tundra
21	Wooded Tundra
22	Mixed Tundra
23	Bare Ground Tundra
24	Snow or Ice

Table 2: IGBP-Modified MODIS 20-category Land Use Categories

Land Use Category	Land Use Description
1	Evergreen Needleleaf Forest
2	Evergreen Broadleaf Forest
3	Deciduous Needleleaf Forest
4	Deciduous Broadleaf Forest
5	Mixed Forests
6	Closed Shrublands
7	Open Shrublands
8	Woody Savannas
9	Savannas
10	Grasslands
11	Permanent Wetlands
12	Croplands

13	Urban and Built-Up
14	Cropland/Natural Vegetation Mosaic
15	Snow and Ice
16	Barren or Sparsely Vegetated
17	Water
18	Wooded Tundra
19	Mixed Tundra
20	Barren Tundra

Table 3: 16-category Soil Categories

Soil Category	Soil Description
1	Sand
2	Loamy Sand
3	Sandy Loam
4	Silt Loam
5	Silt
6	Loam
7	Sandy Clay Loam
8	Silty Clay Loam
9	Clay Loam
10	Sandy Clay
11	Silty Clay
12	Clay
13	Organic Material
14	Water
15	Bedrock
16	Other (land-ice)

WPS Output Fields

Below, a listing of the global attributes and fields that are written to the geogrid program's output files is given. This listing is an abridged version of the output from the ncdump program when run on a typical geo_em.d01.nc file.

```
netcdf geo_em.d01 {
dimensions:
       Time = UNLIMITED ; // (1 currently)
       DateStrLen = 19 ;
       west_east = 73 ;
       south_north = 60 ;
       south_north_stag = 61 ;
       west_east_stag = 74 ;
       land_cat = 24 ;
```

```
       soil_cat = 16 ;
       month = 12 ;
variables:
       char Times(Time, DateStrLen) ;
       float XLAT_M(Time, south_north, west_east) ;
              XLAT_M:units = "degrees latitude" ;
              XLAT_M:description = "Latitude on mass grid" ;
       float XLONG_M(Time, south_north, west_east) ;
              XLONG_M:units = "degrees longitude" ;
              XLONG_M:description = "Longitude on mass grid" ;
       float XLAT_V(Time, south_north_stag, west_east) ;
              XLAT_V:units = "degrees latitude" ;
              XLAT_V:description = "Latitude on V grid" ;
       float XLONG_V(Time, south_north_stag, west_east) ;
              XLONG_V:units = "degrees longitude" ;
              XLONG_V:description = "Longitude on V grid" ;
       float XLAT_U(Time, south_north, west_east_stag) ;
              XLAT_U:units = "degrees latitude" ;
              XLAT_U:description = "Latitude on U grid" ;
       float XLONG_U(Time, south_north, west_east_stag) ;
              XLONG_U:units = "degrees longitude" ;
              XLONG_U:description = "Longitude on U grid" ;
       float CLAT(Time, south_north, west_east) ;
              CLAT:units = "degrees latitude" ;
              CLAT:description = "Computational latitude on mass grid" ;
       float CLONG(Time, south_north, west_east) ;
              CLONG:units = "degrees longitude" ;
              CLONG:description = "Computational longitude on mass grid" ;
       float MAPFAC_M(Time, south_north, west_east) ;
              MAPFAC_M:units = "none" ;
              MAPFAC_M:description = "Mapfactor on mass grid" ;
       float MAPFAC_V(Time, south_north_stag, west_east) ;
              MAPFAC_V:units = "none" ;
              MAPFAC_V:description = "Mapfactor on V grid" ;
       float MAPFAC_U(Time, south_north, west_east_stag) ;
              MAPFAC_U:units = "none" ;
              MAPFAC_U:description = "Mapfactor on U grid" ;
       float MAPFAC_MX(Time, south_north, west_east) ;
              MAPFAC_MX:units = "none" ;
              MAPFAC_MX:description = "Mapfactor (x-dir) on mass grid" ;
       float MAPFAC_VX(Time, south_north_stag, west_east) ;
              MAPFAC_VX:units = "none" ;
              MAPFAC_VX:description = "Mapfactor (x-dir) on V grid" ;
       float MAPFAC_UX(Time, south_north, west_east_stag) ;
              MAPFAC_UX:units = "none" ;
              MAPFAC_UX:description = "Mapfactor (x-dir) on U grid" ;
       float MAPFAC_MY(Time, south_north, west_east) ;
              MAPFAC_MY:units = "none" ;
              MAPFAC_MY:description = "Mapfactor (y-dir) on mass grid" ;
       float MAPFAC_VY(Time, south_north_stag, west_east) ;
              MAPFAC_VY:units = "none" ;
              MAPFAC_VY:description = "Mapfactor (y-dir) on V grid" ;
       float MAPFAC_UY(Time, south_north, west_east_stag) ;
              MAPFAC_UY:units = "none" ;
              MAPFAC_UY:description = "Mapfactor (y-dir) on U grid" ;
       float E(Time, south_north, west_east) ;
              E:units = "-" ;
              E:description = "Coriolis E parameter" ;
       float F(Time, south_north, west_east) ;
              F:units = "-" ;
              F:description = "Coriolis F parameter" ;
       float SINALPHA(Time, south_north, west_east) ;
              SINALPHA:units = "none" ;
```

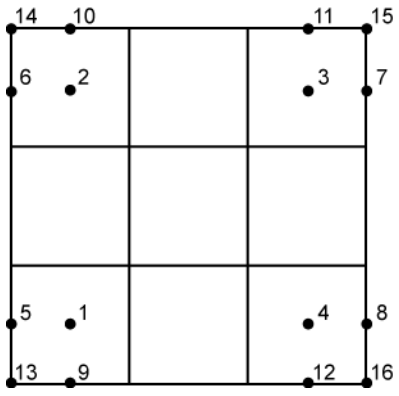
```
       SINALPHA:description = "Sine of rotation angle" ;
float COSALPHA(Time, south_north, west_east) ;
       COSALPHA:units = "none" ;
       COSALPHA:description = "Cosine of rotation angle" ;
float LANDMASK(Time, south_north, west_east) ;
       LANDMASK:units = "none" ;
       LANDMASK:description = "Landmask : 1=land, 0=water" ;
float LANDUSEF(Time, land_cat, south_north, west_east) ;
       LANDUSEF:units = "category" ;
       LANDUSEF:description = "24-category USGS landuse" ;
float LU_INDEX(Time, south_north, west_east) ;
       LU_INDEX:units = "category" ;
       LU_INDEX:description = "Dominant category" ;
float HGT_M(Time, south_north, west_east) ;
       HGT_M:units = "meters MSL" ;
       HGT_M:description = "Topography height" ;
float SLPX(Time, south_north, west_east) ;
       SLPX:units = "-" ;
       SLPX:description = "df/dx" ;
float SLPY(Time, south_north, west_east) ;
       SLPY:units = "-" ;
       SLPY:description = "df/dy" ;
float HGT_U(Time, south_north, west_east_stag) ;
       HGT_U:units = "meters MSL" ;
       HGT_U:description = "Topography height" ;
float HGT_V(Time, south_north_stag, west_east) ;
       HGT_V:units = "meters MSL" ;
       HGT_V:description = "Topography height" ;
float SOILTEMP(Time, south_north, west_east) ;
       SOILTEMP:units = "Kelvin" ;
       SOILTEMP:description = "Annual mean deep soil temperature" ;
float SOILCTOP(Time, soil_cat, south_north, west_east) ;
       SOILCTOP:units = "category" ;
       SOILCTOP:description = "16-category top-layer soil type" ;
float SCT_DOM(Time, south_north, west_east) ;
       SCT_DOM:units = "category" ;
       SCT_DOM:description = "Dominant category" ;
float SOILCBOT(Time, soil_cat, south_north, west_east) ;
       SOILCBOT:units = "category" ;
       SOILCBOT:description = "16-category top-layer soil type" ;
float SCB_DOM(Time, south_north, west_east) ;
       SCB_DOM:units = "category" ;
       SCB_DOM:description = "Dominant category" ;
float ALBEDO12M(Time, month, south_north, west_east) ;
       ALBEDO12M:units = "percent" ;
       ALBEDO12M:description = "Monthly surface albedo" ;
float GREENFRAC(Time, month, south_north, west_east) ;
       GREENFRAC:units = "fraction" ;
       GREENFRAC:description = "Monthly green fraction" ;
float SNOALB(Time, south_north, west_east) ;
       SNOALB:units = "percent" ;
       SNOALB:description = "Maximum snow albedo" ;
float SLOPECAT(Time, south_north, west_east) ;
       SLOPECAT:units = "category" ;
       SLOPECAT:description = "Dominant category" ;
float CON(Time, south_north, west_east) ;
       CON:units = "" ;
       CON:description = "orographic convexity" ;
float VAR(Time, south_north, west_east) ;
       VAR:units = "m" ;
       VAR:description = "stdev of subgrid-scale orographic height" ;
float OA1(Time, south_north, west_east) ;
       OA1:units = "" ;
```

```
              OA1:description = "orographic asymmetry" ;
       float OA2(Time, south_north, west_east) ;
              OA2:units = "" ;
              OA2:description = "orographic asymmetry" ;
       float OA3(Time, south_north, west_east) ;
              OA3:units = "" ;
              OA3:description = "orographic asymmetry" ;
       float OA4(Time, south_north, west_east) ;
              OA4:units = "" ;
              OA4:description = "orographic asymmetry" ;
       float OL1(Time, south_north, west_east) ;
              OL1:units = "fraction" ;
              OL1:description = "effective orographic length" ;
       float OL2(Time, south_north, west_east) ;
              OL2:units = "fraction" ;
              OL2:description = "effective orographic length" ;
       float OL3(Time, south_north, west_east) ;
              OL3:units = "fraction" ;
              OL3:description = "effective orographic length" ;
       float OL4(Time, south_north, west_east) ;
              OL4:units = "fraction" ;
              OL4:description = "effective orographic length" ;


// global attributes:
              :TITLE = "OUTPUT FROM GEOGRID V3.2" ;
              :SIMULATION_START_DATE = "0000-00-00_00:00:00" ;
              :WEST-EAST_GRID_DIMENSION = 74 ;
              :SOUTH-NORTH_GRID_DIMENSION = 61 ;
              :BOTTOM-TOP_GRID_DIMENSION = 0 ;
              :WEST-EAST_PATCH_START_UNSTAG = 1 ;
              :WEST-EAST_PATCH_END_UNSTAG = 73 ;
              :WEST-EAST_PATCH_START_STAG = 1 ;
              :WEST-EAST_PATCH_END_STAG = 74 ;
              :SOUTH-NORTH_PATCH_START_UNSTAG = 1 ;
              :SOUTH-NORTH_PATCH_END_UNSTAG = 60 ;
              :SOUTH-NORTH_PATCH_START_STAG = 1 ;
              :SOUTH-NORTH_PATCH_END_STAG = 61 ;
              :GRIDTYPE = "C" ;
              :DX = 30000.f ;
              :DY = 30000.f ;
              :DYN_OPT = 2 ;
              :CEN_LAT = 34.83001f ;
              :CEN_LON = -81.03f ;
              :TRUELAT1 = 30.f ;
              :TRUELAT2 = 60.f ;
              :MOAD_CEN_LAT = 34.83001f ;
              :STAND_LON = -98.f ;
              :POLE_LAT = 90.f ;
              :POLE_LON = 0.f ;
              :corner_lats = 28.17127f, 44.36657f, 39.63231f, 24.61906f,
28.17842f, 44.37617f, 39.57811f, 24.57806f, 28.03772f, 44.50592f, 39.76032f,
24.49431f, 28.04484f, 44.51554f, 39.70599f, 24.45341f ;
              :corner_lons = -93.64893f, -92.39661f, -66.00165f, -72.6405f, -
93.80048f, -92.59155f, -65.83557f, -72.5033f, -93.65717f, -92.3829f, -65.9313f,
-72.68539f, -93.80841f, -92.57831f, -65.76495f, -72.54843f ;
              :MAP_PROJ = 1 ;
              :MMINLU = "USGS" ;
  :NUM_LAND_CAT             = 24;
              :ISWATER = 16 ;
  :ISLAKE             = -1;
              :ISICE = 24 ;
              :ISURBAN = 1 ;
```

```
                :ISOILWATER = 14 ;
                :grid_id = 1 ;
                :parent_id = 1 ;
                :i_parent_start = 1 ;
                :j_parent_start = 1 ;
                :i_parent_end = 74 ;
                :j_parent_end = 61 ;
                :parent_grid_ratio = 1 ;
                :sr_x = 1 ;
                :sr_y = 1 ;
                :FLAG_MF_XY = 1 ;
}
```

The global attributes `corner_lats` and `corner_lons` contain the lat-lon location of the corners of the domain with respect to different grid staggerings (mass, *u*, *v*, and unstaggered). The locations referred to by each element of the `corner_lats` and `corner_lons` arrays are summarized in the table and figure below.

Array index	**Staggering**	**Corner**
1	Mass	Lower-left
2		Upper-left
3		Upper-right
4		Lower-right
5	U	Lower-left
6		Upper-left
7		Upper-right
8		Lower-right
9	V	Lower-left
10		Upper-left
11		Upper-right
12		Lower-right
13	Unstaggered	Lower-left
14		Upper-left
15		Upper-right
16		Lower-right



In addition to the fields in a geogrid output file (e.g., geo_em.d01.nc), the following fields and global attributes will also be present in a typical output file from the metgrid program, run with the default METGRID.TBL file and meteorological data from NCEP's GFS model.

```
netcdf met_em.d01.2009-01-05_12:00:00 {
dimensions:
       Time = UNLIMITED ; // (1 currently)
       DateStrLen = 19 ;
       west_east = 73 ;
       south_north = 60 ;
       num_metgrid_levels = 27 ;
       num_sm_levels = 4 ;
       num_st_levels = 4 ;
       south_north_stag = 61 ;
       west_east_stag = 74 ;
       z-dimension0012 = 12 ;
       z-dimension0016 = 16 ;
       z-dimension0024 = 24 ;
variables:
       char Times(Time, DateStrLen) ;
       float PRES(Time, num_metgrid_levels, south_north, west_east) ;
              PRES:units = "" ;
              PRES:description = "" ;
       float SOIL_LAYERS(Time, num_st_layers, south_north, west_east) ;
              SM:units = "" ;
              SM:description = "" ;
       float SM(Time, num_sm_levels, south_north, west_east) ;
              SM:units = "" ;
              SM:description = "" ;
       float ST(Time, num_st_levels, south_north, west_east) ;
              ST:units = "" ;
              ST:description = "" ;
       float GHT(Time, num_metgrid_levels, south_north, west_east) ;
              GHT:units = "m" ;
              GHT:description = "Height" ;
       float SNOW(Time, south_north, west_east) ;
              SNOW:units = "kg m-2" ;
              SNOW:description = "Water equivalent snow depth" ;
       float SKINTEMP(Time, south_north, west_east) ;
              SKINTEMP:units = "K" ;
              SKINTEMP:description = "Skin temperature (can use for SST also)" ;
       float SOILHGT(Time, south_north, west_east) ;
              SOILHGT:units = "m" ;
              SOILHGT:description = "Terrain field of source analysis" ;
       float LANDSEA(Time, south_north, west_east) ;
              LANDSEA:units = "proprtn" ;
              LANDSEA:description = "Land/Sea flag (1=land, 0 or 2=sea)" ;
       float SEAICE(Time, south_north, west_east) ;
              SEAICE:units = "proprtn" ;
              SEAICE:description = "Ice flag" ;
       float ST100200(Time, south_north, west_east) ;
              ST100200:units = "K" ;
              ST100200:description = "T 100-200 cm below ground layer (Bottom)"
;
       float ST040100(Time, south_north, west_east) ;
              ST040100:units = "K" ;
              ST040100:description = "T 40-100 cm below ground layer (Upper)" ;
       float ST010040(Time, south_north, west_east) ;
```

```
              ST010040:units = "K" ;
              ST010040:description = "T 10-40 cm below ground layer (Upper)" ;
       float ST000010(Time, south_north, west_east) ;
              ST000010:units = "K" ;
              ST000010:description = "T 0-10 cm below ground layer (Upper)" ;
       float SM100200(Time, south_north, west_east) ;
              SM100200:units = "kg m-3" ;
              SM100200:description = "Soil Moist 100-200 cm below gr layer" ;
       float SM040100(Time, south_north, west_east) ;
              SM040100:units = "kg m-3" ;
              SM040100:description = "Soil Moist 40-100 cm below grn layer" ;
       float SM010040(Time, south_north, west_east) ;
              SM010040:units = "kg m-3" ;
              SM010040:description = "Soil Moist 10-40 cm below grn layer" ;
       float SM000010(Time, south_north, west_east) ;
              SM000010:units = "kg m-3" ;
              SM000010:description = "Soil Moist 0-10 cm below grn layer (Up)" ;
       float PSFC(Time, south_north, west_east) ;
              PSFC:units = "Pa" ;
              PSFC:description = "Surface Pressure" ;
       float RH(Time, num_metgrid_levels, south_north, west_east) ;
              RH:units = "%" ;
              RH:description = "Relative Humidity" ;
       float VV(Time, num_metgrid_levels, south_north_stag, west_east) ;
              VV:units = "m s-1" ;
              VV:description = "V" ;
       float UU(Time, num_metgrid_levels, south_north, west_east_stag) ;
              UU:units = "m s-1" ;
              UU:description = "U" ;
       float TT(Time, num_metgrid_levels, south_north, west_east) ;
              TT:units = "K" ;
              TT:description = "Temperature" ;
       float PMSL(Time, south_north, west_east) ;
              PMSL:units = "Pa" ;
              PMSL:description = "Sea-level Pressure" ;

// global attributes:
              :TITLE = "OUTPUT FROM METGRID V3.2" ;
              :SIMULATION_START_DATE = "2009-01-05_12:00:00" ;
              :WEST-EAST_GRID_DIMENSION = 74 ;
              :SOUTH-NORTH_GRID_DIMENSION = 61 ;
              :BOTTOM-TOP_GRID_DIMENSION = 27 ;
              :WEST-EAST_PATCH_START_UNSTAG = 1 ;
              :WEST-EAST_PATCH_END_UNSTAG = 73 ;
              :WEST-EAST_PATCH_START_STAG = 1 ;
              :WEST-EAST_PATCH_END_STAG = 74 ;
              :SOUTH-NORTH_PATCH_START_UNSTAG = 1 ;
              :SOUTH-NORTH_PATCH_END_UNSTAG = 60 ;
              :SOUTH-NORTH_PATCH_START_STAG = 1 ;
              :SOUTH-NORTH_PATCH_END_STAG = 61 ;
              :GRIDTYPE = "C" ;
              :DX = 30000.f ;
              :DY = 30000.f ;
              :DYN_OPT = 2 ;
              :CEN_LAT = 34.83001f ;
              :CEN_LON = -81.03f ;
              :TRUELAT1 = 30.f ;
              :TRUELAT2 = 60.f ;
              :MOAD_CEN_LAT = 34.83001f ;
              :STAND_LON = -98.f ;
              :POLE_LAT = 90.f ;
              :POLE_LON = 0.f ;
```

```
              :corner_lats = 28.17127f, 44.36657f, 39.63231f, 24.61906f,
28.17842f, 44.37617f, 39.57811f, 24.57806f, 28.03772f, 44.50592f, 39.76032f,
24.49431f, 28.04484f, 44.51554f, 39.70599f, 24.45341f ;
              :corner_lons = -93.64893f, -92.39661f, -66.00165f, -72.6405f, -
93.80048f, -92.59155f, -65.83557f, -72.5033f, -93.65717f, -92.3829f, -65.9313f,
-72.68539f, -93.80841f, -92.57831f, -65.76495f, -72.54843f ;
              :MAP_PROJ = 1 ;
              :MMINLU = "USGS" ;
  :NUM_LAND_CAT             = 24;
              :ISWATER = 16 ;
  :ISLAKE             = -1;
              :ISICE = 24 ;
              :ISURBAN = 1 ;
              :ISOILWATER = 14 ;
              :grid_id = 1 ;
              :parent_id = 1 ;
              :i_parent_start = 1 ;
              :j_parent_start = 1 ;
              :i_parent_end = 74 ;
              :j_parent_end = 61 ;
              :parent_grid_ratio = 1 ;
              :sr_x = 1 ;
              :sr_y = 1 ;
              :NUM_METGRID_SOIL_LEVELS = 4 ;
              :FLAG_METGRID = 1 ;
              :FLAG_SOIL_LAYERS = 1 ;
              :FLAG_SNOW = 1 ;
              :FLAG_PSFC = 1 ;
              :FLAG_SM000010 = 1 ;
              :FLAG_SM010040 = 1 ;
              :FLAG_SM040100 = 1 ;
              :FLAG_SM100200 = 1 ;
              :FLAG_ST000010 = 1 ;
              :FLAG_ST010040 = 1 ;
              :FLAG_ST040100 = 1 ;
              :FLAG_ST100200 = 1 ;
              :FLAG_SLP = 1 ;
              :FLAG_SOILHGT = 1 ;
              :FLAG_MF_XY = 1 ;
}
```

Chapter 4: WRF Initialization

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Introduction

The WRF model has two large classes of simulations that it is able to generate: those with an *ideal* initialization and those utilizing *real* data. The idealized simulations typically manufacture an initial condition file for the WRF model from an existing 1-D or 2-D sounding and assume a simplified analytic orography. The real-data cases usually require pre-processing from the WPS package, which provides each atmospheric and static field with fidelity appropriate to the chosen grid resolution for the model. The WRF model executable itself is not altered by choosing one initialization option over another (idealized *vs*. real), but the WRF model pre-processors (the real.exe and ideal.exe programs) are specifically built based upon a user's selection.

The real.exe and ideal.exe programs are never used together. Both the real.exe and ideal.exe are the programs that are processed just prior to the WRF model run.

The ideal *vs*. real cases are divided as follows:

- Ideal cases – initialization programs named “ideal.exe”
  - 3d
    - em_b_wave - baroclinic wave, 100 km
    - em_heldsuarez – global case with polar filtering, 625 km
    - em_les – large eddy simulation, 100 m
    - em_quarter_ss - super cell, 2 km
  - 2d
    - em_grav2d_x – gravity current, 100 m
    - em_hill2d_x – flow over a hill, 2 km
    - em_seabreeze2d_x – water and land, 2 km, full physics
    - em_squall2d_x – squall line, 250 m
    - em_squall2d_y – transpose of above problem
  - 1d
    - em_scm_xy – single column model, 4 km, full physics

- Real data cases – initialization program named "real.exe"
    - em_real – examples from 4 to 30 km, full physics

The selection of the type of forecast is made when issuing the **`./compile`** statement. When selecting a different case to study, the code must be re-compiled to choose the correct initialization for the model. For example, after configuring the setup for the architecture (with the **`./configure`** command), if the user issues the command **`./compile em_real`**, then the initialization program is built using **`module_initialize_real.F`** as the target module (one of the **`./WRFV3/dyn_em/module_initialize_*.F`** files). Similarly, if the user specifies **`./compile em_les`**, then the Fortran module for the large eddy simulation (**`module_initialize_les.F)`** is automatically inserted into the build for ideal.exe. Note that the WRF forecast model is identical for both of these initialization programs. In each of these initialization modules, the same sort of activities goes on:

- compute a base state / reference profile for geopotential and column pressure
- compute the perturbations from the base state for geopotential and column pressure
- initialize meteorological variables: u, v, potential temperature, vapor mixing ratio
- define a vertical coordinate
- interpolate data to the model's vertical coordinate
- initialize static fields for the map projection and the physical surface; for many of the idealized cases, these are simplified initializations such as map factors set to one, and topography elevation set to zero

Both the real.exe program and ideal.exe programs share a large portion of source code, to handle the following duties:

- read data from the namelist
- allocate space for the requested domain, with model variables specified at run-time
- generate initial condition file

The real-data case does some additional processing:

- read meteorological and static input data from the WRF Preprocessing System (WPS)
- prepare soil fields for use in model (usually, vertical interpolation to the required levels for the specified land surface scheme)
- check to verify soil categories, land use, land mask, soil temperature, sea surface temperature are all consistent with each other
- multiple input time periods are processed to generate the lateral boundary conditions, which are required unless processing a global forecast
- 3d boundary data (u, v, potential temperature, vapor mixing ratio, total geopotential) are coupled with total column pressure

The “real.exe” program may be run as either a serial or a distributed memory job. Since the idealized cases only require that the initialization run for a single time period (no lateral boundary file is required) and are therefore quick to process, all of the “ideal.exe” programs should be run on a single processor. The Makefile for the 2-D cases will not allow the user to build the code with distributed memory parallelism. For large 2-D cases, if the user requires OpenMP, the variables **nproc_x** and **nproc_y** must be set in the **domains** portion of the namelist file **namelist.input** (**nproc_y** must be set to 1, and **nproc_x** then set to the number of processors).

Initialization for Ideal Cases

The program "ideal.exe" is the program in the WRF system to run for a controlled scenario. Typically this program requires no input except for the **namelist.input** and the **input_sounding** files (except for the b_wave case which uses a 2-D binary sounding file). The program outputs the **wrfinput_d01** file that is read by the WRF model executable ("wrf.exe"). Since no external data is required to run the idealized cases, even for researchers interested in real-data cases, the idealized simulations are an easy way to insure that the model is working correctly on a particular architecture and compiler.

Idealized runs can use any of the boundary conditions except "**specified**", and are not, by default, set up to run with sophisticated physics (other than from microphysics). Most have are no radiation, surface fluxes or frictional effects (other than the sea breeze case, LES, and the global Held-Suarez). The idealized cases are mostly useful for dynamical studies, reproducing converged or otherwise known solutions, and idealized cloud modeling.

There are 1-D, 2-D and 3-D examples of idealized cases, with and without topography, and with and without an initial thermal perturbation. The namelist can control the size of domain, number of vertical levels, model top height, grid size, time step, diffusion and damping properties, boundary conditions, and physics options. A large number of existing namelist settings are already found within each of the directories associated with a particular case.

The **input_sounding** file (already in appropriate case directories) can be any set of levels that goes at least up to the model top height (**ztop**) in the namelist. The first line is the surface pressure (hPa), potential temperature (K) and moisture mixing ratio (g/kg). Each subsequent line has five input values: height (meters above sea-level), potential temperature (K), vapor mixing ratio (g/kg), x-direction wind component (m/s), y-direction wind component (m/s). The “ideal.exe” program interpolates the data from the **input_sounding** file, and will extrapolate if not enough data is provided.

The base state sounding for idealized cases is the initial sounding minus the moisture, and so does not have to be defined separately. Note for the baroclinic wave case: a 1-D input sounding is not used because the initial 3-D arrays are read in from the file **input_jet**.

This means for the baroclinic wave case the **`namelist.input`** file cannot be used to change the horizontal or vertical dimensions since they are specified in the **`input_jet`** file.

Making modifications apart from namelist-controlled options or soundings has to be done by editing the Fortran code. Such modifications would include changing the topography, the distribution of vertical levels, the properties of an initialization thermal bubble, or preparing a case to use more physics, such as a land-surface model. The Fortran code to edit is contained in **`./WRFV3/dyn_em/module_initialize_[case].F`**, where **`[case]`** is the case chosen in compilation, e.g. **`module_initialize_squall2d_x.F`**. The subroutine to modify is **`init_domain_rk`**. To change the vertical levels, only the 1-D array **`znw`** must be defined, containing the full levels starting from 1 at k=1 and ending with 0 at k=kde. To change the topography, only the 2-D array **`ht`** must be defined, making sure it is periodic if those boundary conditions are used. To change the thermal perturbation bubble, search for the string "bubble" to locate the code to change.

Each of the ideal cases provides an excellent set of default examples to the user. The method to specify a thermal bubble is given in the super cell case. In the hill2d case, the topography is accounted for properly in setting up the initial 3-D arrays, so that example should be followed for any topography cases. A symmetry example in the squall line cases tests that your indexing modifications are correct. Full physics options are demonstrated in the seabreeze2d_x case.

Available Ideal Test Cases

The available test cases are

1. 2-D squall2d_x (test/em_squall2d_x)
    - 2D squall line (x,z) using Kessler microphysics and a fixed 300 m^2/s viscosity.
    - periodicity condition used in y so that 3D model produces 2D simulation.
    - v velocity should be zero and there should be no variation in y in the results.
2. 2-D squall2d_y (test/em_squall2d_y)
    - Same as squall2d_x, except with (x) rotated to (y).
    - u velocity should be zero and there should be no variation in x in the results.
3. 3-D quarter-circle shear supercell simulation (test/em_quarter_ss).
    - Left and right moving supercells are produced.
    - See the README.quarter_ss file in the test directory for more information.
4. 2-D flow over a bell-shaped hill (x,z) (test/em_hill2d_x)
    - 10 km half-width, 2 km grid-length, 100 m high hill, 10 m/s flow, N=0.01/s, 30 km high domain, 80 levels, open radiative boundaries, absorbing upper boundary.

    - Case is in linear hydrostatic regime, so vertical tilted waves with ~6km vertical wavelength.
5. 3-D baroclinic waves (test/em_b_wave)
    - Baroclinically unstable jet u(y,z) on an f-plane.
    - Symmetric north and south, periodic east and west boundaries.
    - 100 km grid size 16 km top with 4 km damping layer.
    - 41x81 points in (x,y), 64 layers.
6. 2-D gravity current (test/em_grav2d_x)
    - Test case is described in Straka et al, *INT J NUMER METH FL* **17** (1): 1-22 July 15 1993.
    - See the README.grav2d_x file in the test directory.
7. 2-D sea breeze (test/em_seabreeze_x)
    - 2 km grid size, 20 km top, land/water.
    - Can be run with full physics, radiation, surface, boundary layer, land options.
8. 3-D large eddy simulation (test/em_les)
    - 100 m grid size, 2 km top.
    - Surface layer physics with fluxes.
    - Doubly periodic
9. 3-D Held-Suarez (test/em_heldsuarez)
    - global domain, 625 km in x-direction, 556 km in y-direction, 120 km top.
    - Radiation, polar filter above 45^{o}.
    - Period in x-direction, polar boundary conditions in y-direction
10. 1-D single column model (test/em_scm_xy)
    - 4 km grid size, 12 km top
    - Full physics
    - Doubly periodic

Initialization for Real Data Cases

The real-data WRF cases are those that have the input data to the “real.exe” program provided by the WRF Preprocessing System (WPS). This data from the WPS was originally generated from a previously run external analysis or forecast model. The original data was probably in GriB format and was probably ingested into the WPS by first ftp'ing the raw GriB data from one of the national weather agencies’ anonymous ftp sites.

For example, suppose a single-domain WRF forecast is desired with the following criteria:

- 2000 January 24 1200 UTC through January 25 1200 UTC
- the original GriB data is available at 6-h increments

The following files will be generated by the WPS (starting date through ending date, at 6-h increments):

- **met_em.d01.2000-01-24_12:00:00.nc**
- **met_em.d01.2000-01-24_18:00:00.nc**
- **met_em.d01.2000-01-25_00:00:00.nc**
- **met_em.d01.2000-01-25_06:00:00.nc**
- **met_em.d01.2000-01-25_12:00:00.nc**

The convention is to use "**met**" to signify data that is output from the WPS "metgrid.exe" program and input into the "real.exe" program. The "**d01**" portion of the name identifies to which domain this data refers, which permits nesting. The next set of characters is the validation date/time (UTC), where each WPS output file has only a single time-slice of processed data. The file extension suffix "**.nc**" refers to the output format from WPS which must be in netCDF for the "real.exe" program. For regional forecasts, multiple time periods must be processed by "real.exe" so that a lateral boundary file is available to the model. The global option for WRF requires only an initial condition.

The WPS package delivers data that is ready to be used in the WRF system by the "real.exe" program.

- The data adheres to the WRF IO API. Unless you are developing special tools, stick with the netCDF option to communicate between the WPS package and "real.exe".
- The data has already been horizontally interpolated to the correct grid-point staggering for each variable, and the winds are correctly rotated to the WRF model map projection.
- 3-D meteorological data required from the WPS: pressure, u, v, temperature, relative humidity, geopotential height
- 3D soil data from the WPS: soil temperature, soil moisture, soil liquid (optional, depending on physics choices in the WRF model)
- 2D meteorological data from the WPS: sea level pressure, surface pressure, surface u and v, surface temperature, surface relative humidity, input elevation
- 2-D meteorological optional data from WPS: sea surface temperature, physical snow depth, water equivalent snow depth
- 2D static data for the physical surface: terrain elevation, land use categories, soil texture categories, temporally interpolated monthly data, land sea mask, elevation of the input model's topography
- 2D static data for the projection: map factors, Coriolis, projection rotation, computational latitude
- constants: domain size, grid distances, date
- The WPS data may either be isobaric or some more generalized vertical coordinate, where each column is monotonic in pressure
- All 3-D meteorological data (wind, temperature, height, moisture, pressure) must have the same number of levels, and variables must have the exact same levels. It is not acceptable to have more levels for temperature (for example) than height. Likewise, it is not acceptable to have a 925 mb level for the horizontal wind components, but not for moisture.

Real Data Test Case: 2000 January 24/12 through 25/12

- A test data set is accessible from the WRF download page. Under the "WRF Model Test Data" list, select the January data. This is a 74x61, 30-km domain centered over the eastern US.
- Make sure you have successfully built the code (fine-grid nested initial data is available in the download, so the code may be built with the basic nest option), **`./WRFV3/main/real.exe`** and **`./WRFV3/main/wrf.exe`** must both exist.
- In the **`./WRFV3/test/em_real`** directory, copy the namelist for the January case to the default name
    - **`cp namelist.input.jan00 namelist.input`**
- Link the WPS files (the "**`met_em*`**" files from the download) into the **`./WRFV3/test/em_real`** directory.
- For a single processor, to execute the real program, type **`real.exe`** (this should take less than a minute for this small case with five time periods).
- After running the "real.exe" program, the files "**`wrfinput_d01`**" and "**`wrfbdy_d01`**" should be in this directory; these files will be directly used by the WRF model.
- The "wrf.exe" program is executed next (type **`wrf.exe`**), this should take a few minutes (only a 12-h forecast is requested in the namelist file).
- The output file **`wrfout_d01:2000-01-24_12:00:00`** should contain a 12-h forecast at 3-h intervals.

Chapter 5: WRF Model

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Introduction

The WRF model is a fully compressible, and nonhydrostatic model (with a runtime hydrostatic option). Its vertical coordinate is a terrain-following hydrostatic pressure coordinate. The grid staggering is the Arakawa C-grid. The model uses the Runge-Kutta 2nd and 3rd order time integration schemes, and 2nd to 6th order advection schemes in both horizontal and vertical. It uses a time-split small step for acoustic and gravity-wave modes. The dynamics conserves scalar variables.

The WRF model code contains several initialization programs (*ideal.exe* and *real.exe*; see Chapter 4), a numerical integration program (*wrf.exe*), and a program to do one-way nesting (*ndown.exe*). The WRF model Version 3 supports a variety of capabilities. These include

- Real-data and idealized simulations
- Various lateral boundary condition options for real-data and idealized simulations
- Full physics options, and various filter options
- Positive-definite advection scheme
- Non-hydrostatic and hydrostatic (runtime option)
- One-way, two-way nesting and moving nest
- Three-dimensional analysis nudging
- Observation nudging
- Regional and global applications
- Digital filter initialization

Other References

- WRF tutorial presentation: http://www.mmm.ucar.edu/wrf/users/supports/tutorial.html
- WRF-ARW Tech Note: http://www.mmm.ucar.edu/wrf/users/pub-doc.html
- Chapter 2 of this document for software requirement.

Installing WRF

Before compiling WRF code on a computer, check to see if the netCDF library is installed. This is because one of the supported WRF I/O options is netCDF, and it is the one commonly used, and supported by the post-processing programs. If the netCDF is installed in a directory other than `/usr/local/`, then find the path, and use the environment variable NETCDF to define where the path is. To do so, type

```
setenv NETCDF path-to-netcdf-library
```

Often the netCDF library and its include/ directory are collocated. If this is not the case, create a directory, link both netCDF lib and include directories in this directory, and use environment variable to set the path to this directory. For example,

```
netcdf_links/lib -> /netcdf-lib-dir/lib
netcdf_links/include -> /where-include-dir-is/include

setenv NETCDF /directory-where-netcdf_links-is/netcdf_links
```

If the netCDF library is not available on the computer, it needs to be installed first. NetCDF source code or pre-built binary may be downloaded from and installation instruction can be found on the Unidata Web page at http://www.unidata.ucar.edu/.

***Hint*:** for Linux users:

If PGI, Intel or g95 compiler are used on a Linux computer, make sure netCDF is installed using the same compiler. Use NETCDF environment variable to point to the PGI/Intel/g95 compiled netCDF library.

Hint: If using netCDF-4, make sure that the new capabilities (such as parallel I/O based on HDF5) are not activated at the install time.

WRF source code tar file can be downloaded from http://www.mmm.ucar.edu/wrf/download/get_source.html. Once the tar file is unzipped (`gunzip WRFV3.TAR.gz`), and untared (`tar -xf WRFV3.TAR`), and it will create a WRFV3/ directory. This contains:

`Makefile`	Top-level makefile
`README`	General information about WRF/ARW core
`README_test_cases`	Explanation of the test cases
`README.NMM`	General information for WRF/NMM core
`README.rsl_output`	For NMM
`Registry/`	Directory for WRF Registry files
`arch/`	Directory where compile options are gathered
`clean`	script to clean created files, executables
`compile`	script for compiling WRF code
`configure`	script to create the *configure.wrf* file for compile
`chem/`	WRF chemistry, supported by NOAA/GSD
`dyn_em/`	Directory for ARW dynamics and numerics
`dyn_exp/`	Directory for a 'toy' dynamic core
`dyn_nmm/`	Directory for NMM dynamics and numerics, supported by DTC
`external/`	Directory that contains external packages, such as those for IO, time keeping and MPI
`frame/`	Directory that contains modules for WRF framework
`inc/`	Directory that contains include files
`main/`	Directory for main routines, such as wrf.F, and all executables after compilation
`phys/`	Directory for all physics modules
`run/`	Directory where one may run WRF
`share/`	Directory that contains mostly modules for WRF mediation layer and WRF I/O
`test/`	Directory that contains test case directories, may be used to run WRF
`tools/`	Directory that contains tools for developers

The steps to compile and run the model are:

1. configure: generate a configuration file for compilation

2. compile: compile the code
3. run the model

Go to WRFV3 (top) directory and type

```
./configure
```

and a list of choices for your computer should appear. These choices range from compiling for a single processor job (serial), to using OpenMP shared-memory (smpar) or distributed-memory parallelization (dmpar) options for multiple processors, or combination of shared-memory and distributed memory options (dm+sm). When a selection is made, a second choice for compiling nesting will appear. For example, on a Linux computer, the above steps may look like:

```
> setenv NETCDF /usr/local/netcdf-pgi
> ./configure

checking for perl5... no
checking for perl... found /usr/bin/perl (perl)
Will use NETCDF in dir: /usr/local/netcdf-pgi
PHDF5 not set in environment. Will configure WRF for use without.
$JASPERLIB or $JASPERINC not found in environment, configuring to build
without grib2 I/O...
------------------------------------------------------------------------
Please select from among the following supported platforms.

1.  Linux i486 i586 i686, gfortran compiler with gcc  (serial)
2.  Linux i486 i586 i686, gfortran compiler with gcc  (smpar)
3.  Linux i486 i586 i686, gfortran compiler with gcc  (dmpar)
4.  Linux i486 i586 i686, gfortran compiler with gcc  (dm+sm)
5.  Linux i486 i586 i686, g95 compiler with gcc  (serial)
6.  Linux i486 i586 i686, g95 compiler with gcc  (dmpar)
7.  Linux i486 i586 i686, PGI compiler with gcc  (serial)
8.  Linux i486 i586 i686, PGI compiler with gcc  (smpar)
9.  Linux i486 i586 i686, PGI compiler with gcc  (dmpar)
10.  Linux i486 i586 i686, PGI compiler with gcc  (dm+sm)
11.  Linux x86_64 i486 i586 i686, ifort compiler with icc (non-SGI
installations)  (serial)
12.  Linux x86_64 i486 i586 i686, ifort compiler with icc (non-SGI
installations)  (smpar)
13.  Linux x86_64 i486 i586 i686, ifort compiler with icc (non-SGI
installations)  (dmpar)
14.  Linux x86_64 i486 i586 i686, ifort compiler with icc (non-SGI
installations)  (dm+sm)
15.  Linux i486 i586 i686 x86_64, PathScale compiler with pathcc
(serial)
16.  Linux i486 i586 i686 x86_64, PathScale compiler with pathcc
(dmpar)

Enter selection [1-16] : 9

Compile for nesting? (0=no nesting, 1=basic, 2=preset moves, 3=vortex
following) [default 0]: 1
```

Enter appropriate options that are best for your computer and application.

Alternatively, one may type

```
> ./configure arw
```

When the return key is hit, a `configure.wrf` file will be created. Edit compile options/paths, if necessary.

Hint: It is helpful to start with something simple, such as the serial build. If it is successful, move on to build smpar or dmpar code. Remember to type 'clean –a' between each build.

Hint: If you anticipate generating a netCDF file that is larger than 2Gb (whether it is a single or multi time period data [e.g. model history]) file), you may set the following environment variable to activate the large-file support option from netCDF:

```
setenv WRFIO_NCD_LARGE_FILE_SUPPORT 1
```

To compile the code, type

```
./compile
```

and the following choices will appear:

```
Usage:

compile wrf           compile wrf in run dir (Note, no real.exe,
ndown.exe or ideal.exe generated)

or choose a test case (see README_test_cases for details):

    compile em_b_wave
    compile em_esmf_exp (example only)
    compile em_grav2d_x
    compile em_heldsuarez
    compile em_hill2d_x
    compile em_les
    compile em_quarter_ss
    compile em_real
    compile em_seabreeze2d_x
    compile em_squall2d_x
    compile em_squall2d_y
    compile exp_real (example of a toy solver)
    compile nmm_real (NMM solver)

compile -h              help message
```

where **em** stands for the Advanced Research WRF dynamic solver (which currently is the '**E**ulerian **m**ass-coordinate' solver). Type one of the above to compile. When you switch

from one test case to another, you must type one of the above to recompile. The recompile is necessary to create a new initialization executable (i.e. `real.exe`, and `ideal.exe` - there is a different `ideal.exe` for each of the idealized test cases), while `wrf.exe` is the same for all test cases.

If you want to remove all object files (except those in `external/` directory) and executables, type `'clean'`.

Type `'clean -a'` to remove built files in ALL directories, including `configure.wrf` (the original `configure.wrf` will be saved to `configure.wrf.backup`). This is recommended if you make any mistake during the process, or if you have edited the `configure.wrf` or `Registry.EM` file.

Hint: If you have trouble compiling routines like solve_em.F, you can try to run the *`configure`* script with optional argument `'-s'`, i.e.

```
./configure -s
```

This will configure to compile solve_em.F and a few other routines with reduced optimization.

If you would like to turn off optimization for all the code, say during code development and debugging, you can run *`configure`* script with option *`'-d'`*:

```
./configure -d
```

a. Idealized case

For any 2D test cases (labeled in the case names), serial or OpenMP (smpar) compile options must be used. Suppose you would like to compile and run the 2-dimensional squall case, type

```
./compile em_squall2d_x >& compile.log
```

After a successful compilation, you should have two executables created in the **`main`**/ directory: **`ideal.exe`** and **`wrf.exe`**. These two executables will be linked to the corresponding `test`/`case_name` and `run`/ directories. `cd` to either directory to run the model.

It is a good practice to save the entire compile output to a file. When the executables were not present, this output is useful to help diagnose the compile errors.

b. Real-data case

For a real-data case, type

```
./compile em_real >& compile.log &
```

When the compile is successful, it will create three executables in the **main**/directory: `ndown.exe`, `real.exe` and `wrf.exe`.

`real.exe`: for WRF initialization of real data cases
`ndown.exe` : for one-way nesting
`wrf.exe` : WRF model integration

Like in the idealized cases, these executables will be linked to `test/em_real` and `run/` directories. `cd` to one of these two directories to run the model.

Running WRF

One may run the model executables in either the `run/` directory, or the `test/case_name` directory. In either case, one should see executables, `ideal.exe` or `real.exe` (and `ndown.exe`), and `wrf.exe`, linked files (mostly for real-data cases), and one or more `namelist.input` files in the directory.

Hint: If you would like to run the model executables in a different directory, copy or link the files in `test/em_*` directory to that directory, and run from there.

a. Idealized case

Suppose the test case `em_squall2d_x` is compiled, to run, type

```
cd test/em_squall2d_x
```

Edit `namelist.input` file (see `README.namelist` in `WRFV3/run/` directory or its Web version) to change length of integration, frequency of output, size of domain, timestep, physics options, and other parameters.

If you see a script in the test case directory, called `run_me_first.csh`, run this one first by typing:

```
./run_me_first.csh
```

This links some physics data files that might be needed to run the case.

To run the initialization program, type

```
./ideal.exe
```

This program will typically read an input sounding file located in that directory, and generate an initial condition file `wrfinput_d01`. All idealized cases do not require lateral boundary file because of the boundary condition choices they use, such as the periodic option. If the job is run successfully, the last thing it prints should be: '`wrf: SUCCESS COMPLETE IDEAL INIT`'.

To run the model and save the standard output to a file, type

```
./wrf.exe >& wrf.out &
```

or for a 3D test case compiled with MPI (dmpar) option,

```
mpirun -np 4 ./wrf.exe
```

If successful, the wrf output file will be written to a file named `wrfout_d01_0001-01-01_00:00:00`.

Pairs of `rsl.out.*` and `rsl.error.*` files will appear with any MPI runs. These are standard out and error files. Note that the execution command for MPI runs may be different on different machines and for different MPI installation. Check the user manual.

If the model run is successful, the last thing printed in '`wrf.out`' or `rsl.*.0000` file should be: '`wrf: SUCCESS COMPLETE WRF`'. Output files `wrfout_d01_0001-01-01*` and `wrfrst*` should be present in the run directory, depending on how namelist variables are specified for output. The time stamp on these files originates from the start times in the namelist file.

b. Real-data case

To make a real-data case run, `cd` to the working directory by typing

```
cd test/em_real (or cd run)
```

Start with a `namelist.input` template file in the directory, edit it to match your case.

Running a real-data case requires successfully running the **WRF Preprocessing System** programs (or WPS). Make sure `met_em.*` files from WPS are seen in the run directory (either link or copy the files):

```
cd test/em_real
ls -l ../../../WPS/met_em*
ln -s ../../..WPS/met_em* .
```

Make sure you edit the following variables in `namelist.input` file:

`num_metgrid_levels`: number of_ incoming data levels (can be found by using `ncdump` command on `met_em.*` file)

`eta_levels`: model *eta* levels from 1 to 0, if you choose to do so. If not, `real` will compute a nice set of *eta* levels. The computed eta levels have 7 half levels in the lowest 1 km or so, and stretches to constant δz.

Other options for use to assist vertical interpolation are:

`use_surface:` whether to use surface input data
`extrap_type:` vertical extrapolation of non-temperature fields
`t_extrap_type:` vertical extrapolation for potential temperature
`use_levels_below_ground:` use levels below input surface level
`force_sfc_in_vinterp`: force vertical interpolation to use surface data
`lowest_lev_from_sfc`: place surface data in the lowest model level
`p_top_requested`: pressure top used in the model, default is 5000 Pa
`interp_type`: vertical interpolation method: linear in p(default) or log(p)
`lagrange_order`: vertical interpolation order, linear (default) or quadratic
`zap_close_levels`: allow surface data to be used if it is close to a constant pressure level.
`smooth_cg_topo`: smooth topography on the outer rows and columns in domain 1.
`use_tavg_for_tsk`: whether to use diurnally averaged surface temp as skin temp. The diurnall averaged surface temp can be computed using WPS utility `avg_tsfc.exe`. May use this option when SKINTEMP is not present.

Other minimum set of namelist variables to edit are:

`start_*, end_*:` start and end times for data processing and model integration
`interval_seconds:` input data interval for boundary conditions
`time_step:` model time step, and can be set as large as 6*DX (in km)
`e_ws, e_sn, e_vert:` domain dimensions in west-east, south-north and vertical
`dx, dy:` model grid distance in meters

To run real-data initialization program compiled using serial or OpenMP (smpar) options, type

```
./real.exe >& real.out
```

Successful completion of the job should have ‘real_em: SUCCESS EM_REAL INIT’ printed at the end of real.out file. It should also produce wrfinput_d01 and wrfbdy_d01 files. In real data case, both files are required.

Run WRF model by typing

```
./wrf.exe
```

A successful run should produce one or several output files with names like `wrfout_d<domain>_<date>` (where `<domain>` represents domain ID, and

<date> represents a date string with the format yyyy-mm-dd_hh:mm:ss. For example, if you start the model at 1200 UTC, January 24 2000, then your first output file should have the name:

```
wrfout_d01_2000-01-24_12:00:00
```

The time stamp on the file name is always the first time the output file is written. It is always good to check the times written to the output file by typing:

```
ncdump -v Times wrfout_d01_2000-01-24_12:00:00
```

You may have other wrfout files depending on the namelist options (how often you split the output files and so on using namelist option frames_per_outfile).You may also create restart files if you have restart frequency (restart_interval in the namelist.input file) set within your total integration length. The restart file should have names like

```
wrfrst_d<domain>_<date>
```

The time stamp on a restart file is the time that restart file is valid at.

For DM (distributed memory) parallel systems, some form of **mpirun** command will be needed to run the executables. For example, on a Linux cluster, the command to run MPI code and using 4 processors may look like:

```
mpirun -np 4 ./real.exe
mpirun -np 4 ./wrf.exe
```

On some IBMs, the command may be:

```
poe ./real.exe
poe ./wrf.exe
```

for a batch job, and

```
poe ./real.exe -rmpool 1 -procs 4
poe ./wrf.exe -rmpool 1 -procs 4
```

for an interactive run. (Interactive MPI job is not an option on NCAR IBM *bluefire*)

c. Restart Run

A restart run allows a user to extend a run to a longer simulation period. It is effectively a continuous run made of several shorter runs. Hence the results at the end of one or more restart runs should be identical to a single run without any restart.

In order to do a restart run, one must first create restart file. This is done by setting namelist variable restart_interval (unit is in minutes) to be equal to or less than

the simulation length in the first model run, as specified by `run_*` variables or `start_*` and `end_*` times. When the model reaches the time to write a restart file, a restart file named `wrfrst_d<domain>_<date>` will be written. The date string represents the time when the restart file is valid.

When one starts the restart run, edit the `namelist.input` file, so that your `start_*` time will be set to the restart time (which is the time the restart file is written). The other namelist variable one must set is `restart`, this variable should be set to .true. for a restart run.

In summary, these namelists should be modified:

`start_*, end_*:`	start and end times for restart model integration
`restart:`	logical to indicate whether the run is a restart or not

***Hint*:** Typically the restart file is a lot bigger in size than the history file, hence one may find that even it is ok to write a single model history output time to a file in netCDF format (`frame_per_outfile=1`), it may fail to write a restart file. This is because the basic netCDF file support is only 2Gb. There are two solutions to the problem. The first is to simply set namelist option `io_form_restart = 102` (instead of 2), and this will force the restart file to be written into multiple pieces, one per processor. As long as one restarts the model using the same number of processors, this option works well (and one should restart the model with the same number of processors in any case). The second solution is to recompile the code using the netCDF large file support option (see section on "Installing WRF" in this chapter).

d. Two-way Nested Runs

A two-way nested run is a run where multiple domains at different grid resolutions are run simultaneously and communicate with each other: The coarser domain provides boundary values for the nest, and the nest feeds its calculation back to the coarser domain. The model can handle multiple domains at the same nest level (no overlapping nest), and multiple nest levels (telescoping).

When preparing for a nested run, make sure that the code is compiled with basic nest options (option 1).

Most of options to start a nest run are handled through the namelist. ***All variables in the*** `namelist.input` ***file that have multiple columns of entries need to be edited with caution***. Do start with a namelist template. The following are the key namelist variables to modify:

`start_*, end_*`: start and end simulation times for the nest

input_from_file: whether a nest requires an input file (e.g. wrfinput_d02). This is typically used for a real data case, since the nest input file contains nest topography and land information.

fine_input_stream: which fields from the nest input file are used in nest initialization. The fields to be used are defined in the Registry.EM. Typically they include static fields (such as terrain, landuse), and masked surface fields (such as skin temperature, soil moisture and temperature). Useful for nest starting at a later time than the coarse domain.

max_dom: the total number of domains to run. For example, if you want to have one coarse domain and one nest, set this variable to 2.

grid_id: domain identifier that is used in the wrfout naming convention. The most coarse grid must have grid_id of 1.

parent_id: used to indicate the parent domain of a nest. grid_id value is used.

i_parent_start/j_parent_start: lower-left corner starting indices of the nest domain in its parent domain. These parameters should be the same as in namelist.wps.

parent_grid_ratio: integer parent-to-nest domain grid size ratio. Typically odd number ratio is used in real-data applications.

parent_time_step_ratio: integer time-step ratio for the nest domain. It may be different from the parent_grid_ratio, though they are typically set the same.

feedback: this is the key setup to define a two-way nested (or one-way nested) run. When feedback is on, the values of the coarse domain are overwritten by the values of the variables (average of cell values for mass points, and average of the cell-face values for horizontal momentum points) in the nest at the coincident points. For masked fields, only the single point value at the collocating points is fedback. If the parent_grid_ratio is even, an arbitrary choice of southwest corner point value is used for feedback. This is the reason it is better to use odd parent_grid_ratio with this option. When feedback is off , it is equivalent to a one-way nested run, since nest results are not reflected in the parent domain.

smooth_option: this a smoothing option for the parent domain in area of the nest if *feedback* is on. Three options are available: 0 = no smoothing; 1 = 1-2-1 smoothing; 2 = smoothing-desmoothing.

3-D Idealized Cases

For 3-D idealized cases, no nest input files are required. The key here is the specification of the namelist.input file. What the model does is to interpolate all variables required in the nest from the coarse domain fields. Set

input_from_file = F, F

Real Data Cases

For real-data cases, three input options are supported. The first one is similar to running the idealized cases. That is to have all fields for the nest interpolated from the coarse domain (`input_from_file = T, F`). The disadvantage of this option is obvious, one will not benefit from the higher resolution static fields (such as terrain, landuse, and so on).

The second option is to set `input_from_file = T` for each domain, which means that the nest will have a nest wrfinput file to read in. The limitation of this option is that this only allows the nest to start at the same time as the coarse domain.

The third option is in addition to setting `input_from_file = T` for each domain, also set `fine_input_stream = 2` for each domain. Why a value of 2? This is based on the Registry setting, which designates certain fields to be read in from auxiliary input stream number 2. This option allows the nest initialization to use 3-D meteorological fields interpolated from the coarse domain, static fields and masked, time-varying surface fields from the nest wrfinput. It hence allows a nest to start at a later time than hour 0. Setting `fine_input_stream = 0` is equivalent to the second option.

To run `real.exe` for a nested run, one must first run WPS and create data for all the nests. Suppose WPS is run for a 24 hour period, two-domain nest case starting 1200 UTC Jan 24 2000, and these files should be generated in a WPS directory:

```
met_em.d01.2000-01-24_12:00:00
met_em.d01.2000-01-24_18:00:00
met_em.d01.2000-01-25_00:00:00
met_em.d01.2000-01-25_06:00:00
met_em.d01.2000-01-25_12:00:00
met_em.d02.2000-01-24_12:00:00
```

Typically only the first time period of the nest input file is needed to create nest wrfinput file. Link or move all these files to the run directory.

Edit the `namelist.input` file and set the correct values for all relevant variables, described on the previous pages (in particular, set `max_dom = 2`, for the total number of domains to run), as well as physics options. Type the following to run:

```
./real.exe >& real.out
```
or
```
mpirun -np 4 ./real.exe
```

If successful, this will create all input files for coarse as well as nest domains. For a two-domain example, these are:

```
wrfinput_d01
wrfinput_d02
wrfbdy_d01
```

To run WRF, type

```
./wrf.exe
```
or
```
mpirun -np 4 ./wrf.exe
```

If successful, the model should create wrfout files for both domain 1 and 2:

```
wrfout_d01_2000-01-24_12:00:00
wrfout_d02_2000-01-24_12:00:00
```

e. One-way Nested Run Using ndown

WRF supports two separate one-way nested option. In this section, one-way nesting is defined as a finer-grid-resolution run made as a subsequent run after the coarser-grid-resolution run, where the `ndown` program is run in between the two simulations. The initial and lateral boundary conditions for this finer-grid run are obtained from the coarse grid run, together with input from higher resolution terrestrial fields (e.g. terrain, landuse, etc.), and masked surface fields (such as soil temperature and moisture). The program that performs this task is `ndown.exe`. Note that the use of this program requires the code to be compiled for nesting.

When one-way nesting is used, the coarse-to-fine grid ratio is only restricted to be an integer. An integer less than or equal to 5 is recommended. Frequent output (e.g. hourly) from the coarse grid run is also recommended to provide better boundary specifications.

A caveat with using `ndown` for one-way nesting is that the microphysics variables are not used for boundary conditions; they are only in the initial conditions. If that is important to you, use two-way nesting option instead.

To make a one-way nested run involves these steps:

1) Generate a coarse-grid model output
2) Make temporary fine-grid initial condition `wrfinput_d01` file (note that only a single time period is required, valid at the desired start time of the fine-grid domain)
3) Run program `ndown`**,** with coarse-grid model output and a fine-grid initial condition to generate fine grid initial and boundary conditions, similar to the output from the `real.exe` program)
4) Run the fine-grid simulation

To compile, choose an option that supports nesting.

Step 1: Make a coarse grid run

This is no different than any of the single domain WRF run as described above.

Step 2: Make a temporary fine grid initial condition file

The purpose of this step is to ingest higher resolution terrestrial fields and corresponding land-water masked soil fields.

Before doing this step, WPS should be run for one coarse and one nest domains (this helps to line up the nest with the coarse domain), and for the one time period the one-way nested run is to start. This generates a WPS output file for the nested domain (domain 2): `met_em.d02.<date>`.

- Rename `met_em.d02.*` to `met.d01.*` for the single requested fine-grid start time. Move the original domain 1 WPS output files before you do this.
- Edit the `namelist.input` file for fine-grid domain (pay attention to column 1 only) and edit in the correct start time, grid dimensions.
- Run `real.exe` for this domain. This will produce a `wrfinput_d01` file.
- Rename this `wrfinput_d01` file to `wrfndi_d02`.

Step 3: Make the final fine-grid initial and boundary condition files

- Edit `namelist.input` again, and this time one needs to edit two columns: one for dimensions of the coarse grid, and one for the fine grid. Note that the boundary condition frequency (namelist variable `interval_seconds`) is the time in seconds between the coarse-grid model output times. Since V3.2, one must also specify `io_form_auxinput2` = 2 to run `ndown` successfully.
- Run `ndown.exe`, with inputs from the coarse grid `wrfout` file(s), and `wrfndi_d02` file generated from Step 2 above. This will produce `wrfinput_d02` and `wrfbdy_d02` files.

- If one desires to refine vertical resolution when running `ndown`, set `vert_refine_fact =` ***`integer`*** (new in V3.2). There are no other changes required in the namelist or in the procedure.

- Another way to refine vertical resolution is to use utility program `v_interp` (see chapter for 'Utilities and Tools' for details.

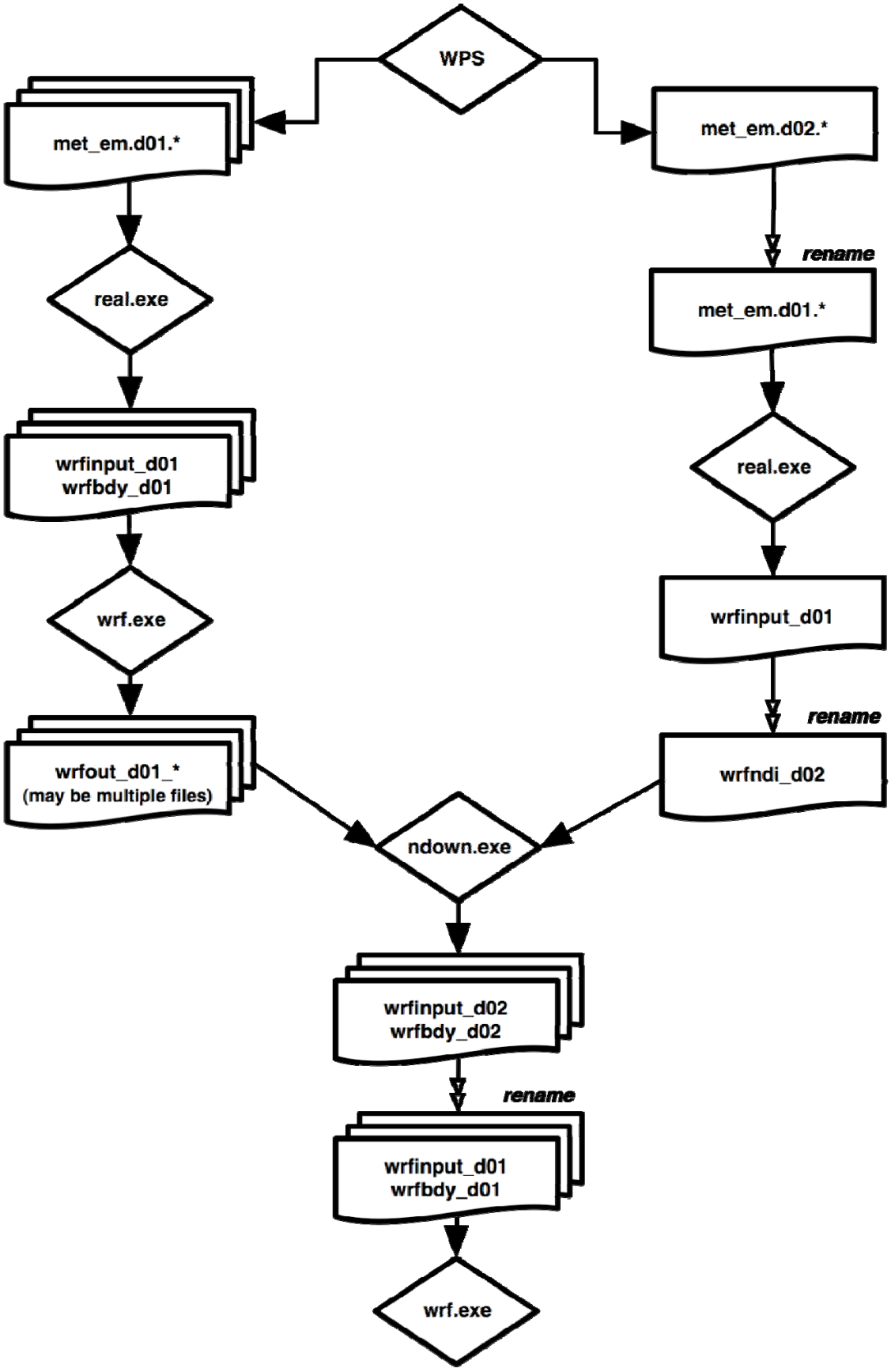
Note that program `ndown` may be run serially or in MPI, depending on the selected compile option. The `ndown` program must be built to support nesting, however. To run the program, type,

```
./ndown.exe
```
or
```
mpirun -np 4 ./ndown.exe
```

Step 4: Make the fine-grid WRF run

- Rename `wrfinput_d02` and `wrfbdy_d02` to `wrfinput_d01` and `wrfbdy_d01`, respectively.
- Edit `namelist.input` one more time, and it is now for the fine-grid domain only.
- Run WRF for this grid.

The figure on the next page summarizes the data flow for a one-way nested run using program `ndown`.


WPS
met_em.d01.*
real.exe
wrfinput_d01
wrfbdy_d01
wrf.exe
wrfout_d01_*
(may be multiple files)
met_em.d02.*
rename
met_em.d01.*
real.exe
wrfinput_d01
rename
wrfndi_d02
ndown.exe
wrfinput_d02
wrfbdy_d02
rename
wrfinput_d01
wrfbdy_d01
wrf.exe

f. Moving-Nested Run

Two types of moving tests are allowed in WRF. In the first option, a user specifies the nest movement in the namelist. The second option is to move the nest automatically based on an automatic vortex-following algorithm. This option is designed to follow the movement of a well-defined tropical cyclone.

To make the specified moving nested run, select the right nesting compile option (option 'preset moves'). Note that code compiled with this option will not support static nested runs. To run the model, only the coarse grid input files are required. In this option, the nest initialization is defined from the coarse grid data - no nest input is used. In addition to the namelist options applied to a nested run, the following needs to be added to namelist section `&domains`:

`num_moves`: the total number of moves one can make in a model run. A move of any domain counts against this total. The maximum is currently set to 50, but it can be changed by change MAX_MOVES in `frame/module_driver_constants.F`.

`move_id`: a list of nest IDs, one per move, indicating which domain is to move for a given move.

`move_interval`: the number of minutes since the beginning of the run that a move is supposed to occur. The nest will move on the next time step after the specified instant of model time has passed.

`move_cd_x,move_cd_y`: distance in number of grid points and direction of the nest move(positive numbers indicating moving toward east and north, while negative numbers indicating moving toward west and south).

Parameter `max_moves` is set to be 50, but can be modified in source code file *frame/module_driver_constants.F* if needed.

To make the automatic moving nested runs, select the 'vortex-following' option when configuring. Again note that this compile would only support auto-moving nest, and will not support the specified moving nested run or static nested run at the same time. Again, no nest input is needed. If one wants to use values other than the default ones, add and edit the following namelist variables in `&domains` section:

`vortex_interval`: how often the vortex position is calculated in minutes (default is 15 minutes).

`max_vortex_speed`: used with *vortex_interval* to compute the radius of search for the new vortex center position (default is 40 m/sec).

`corral_dist`: the distance in number of coarse grid cells that the moving nest is allowed to come near the coarse grid boundary (default is 8). This parameter can be used to center the telescoped nests so that all nests are moved together with the storm.

`track_level`: the pressure level (in Pa) where the vortex is tracked.

time_to_move: the time (in minutes) to move a nest. This option may help with the case when the storm is still too weak to be tracked by the algorithm.

When automatic moving nest is employed, the model dumps the vortex center location, with minimum mean sea-level pressure and maximum 10 m winds in standard out file (e.g. rsl.out.0000). Tying 'grep ATCF rsl.out.0000' will produce a list of storm information at 15 minutes interval:

```
ATCF    2007-08-20_12:00:00           20.37   -81.80     929.7      133.9
ATCF    2007-08-20_12:15:00           20.29   -81.76     929.3      133.2
```

In both types of moving nest runs, the initial location of the nest is specified through i_parent_start and j_parent_start in the namelist.input file.

The automatic moving nest works best for well-developed vortex.

g. Analysis Nudging Runs (Upper-Air and/or Surface)

Prepare input data to WRF as usual using WPS. If nudging is desired in the nest domains, make sure all time periods for all domains are processed in WPS. For surface-analysis nudging (new in Version 3.1), OBSGRID needs to be run after METGRID, and it will output a wrfsfdda_d01 file that the WRF model reads for this option.

Set the following options before running real.exe, in addition to others described earlier (see namelist template namelist.input.grid_fdda in test/em_real/ directory for guidance):

```
grid_fdda = 1
grid_sfdda = 1
```

Run real.exe as before, and this will create, in addition to wrfinput_d0* and wrfbdy_d01 files, a file named 'wrffdda_d0*'. Other grid nudging namelists are ignored at this stage. But it is a good practice to fill them all before one runs real. In particular, set

```
gfdda_inname    =  "wrffdda_d<domain>"
gfdda_interval  = time interval of input data in minutes
gfdda_end_h     = end time of grid nudging in hours

sgfdda_inname    =  "wrfsfdda_d<domain>"
sgfdda_interval  = time interval of input data in minutes
sgfdda_end_h     = end time of surface egrid nudging in hours
```

See http://www.mmm.ucar.edu/wrf/users/wrfv2/How_to_run_grid_fdda.html and README.grid_fdda in WRFV3/test/em_real/ for more information.

Spectral Nudging is a new upper-air nudging option in Version 3.1. This selectively nudges the coarser scales only, but is otherwise set up the same way as grid-nudging. This option also nudges geopotential height. The wave numbers defined here are the number of waves contained in the domain, and the number is the maximum one that is nudged.

```
grid_fdda = 2
xwavenum = 3
ywavenum = 3
```

h. Observation Nudging Run

In addition to the usual input data preparation using WPS, station observation files are required. See http://www.mmm.ucar.edu/wrf/users/wrfv2/How_to_run_obs_fdda.html for instructions. The observation file names expected by WRF are `OBS_DOMAIN101` for domain 1, and `OBS_DOMAIN201` for domain 2, etc.

Observation nudging is activated in the model by the following namelists:

```
obs_nudge_opt = 1
fdda_start    = 0 (obs nudging start time in minutes)
fdda_end      = 360 (obs nudging end time in minutes)
```

Look for example to set other obs nudging namelist variables in namelist template `namelist.input.obs_fdda` in `test/em_real/` directory. See http://www.mmm.ucar.edu/wrf/users/wrfv2/How_to_run_obs_fdda.html and `README.obs_fdda` in `WRFV3/test/em_real/` for more information.

i. Global Run

WRFV3 begins to support global capability. To make a global run, run WPS starting with namelist template `namelist.wps.gloabl`. Set `map_proj = 'lat-lon',` and grid dimensions `e_we` and `e_sn` without setting `dx` and `dy` in `namelist.wps`. The `geogrid` program will calculate grid distances and their values can be found in the global attribute section of `geo_em.d01.nc` file. Type `ncdump -h geo_em.d01.nc` to find out the grid distances, which will be needed in filling out WRF's `namelist.input` file. Grid distances in x and y directions may be different, but it is best they are set similarly or the same. WRF and WPS assume earth is a sphere, and its radius is 6370 km. There is no restrictions on what to use for grid dimensions, but for effective use of the polar filter in WRF, the east-west dimension should be set to $2^P*3^Q*5^R+1$ (where P, Q, and R are any integers, including 0).

Run the rest of WPS programs as usual but only for one time period. This is because the domain covers the entire globe, lateral boundary conditions are no longer needed.

Run program `real.exe` as usual and for one time period only. Lateral boundary file `wrfbdy_d01` is not needed.

Copy over `namelist.input.global` to `namelist.input`, and edit it. Run the model as usual.

Note that since this is a new option in the model, use it with caution. Not all options have been tested. For example, all filter options have not been tested, and positive-definite options are not working for lat-lon grid.

As an extension to the global lat-lon grid, regional domain can be set using lat-lon grid too. To do so, one need to set both grid dimensions, and grid distances in degrees. Again `geogrid` will calculate the grid distance assuming the earth is a sphere and its radius is 6370 km. Find grid distance in meters in the netcdf file, and use the value for WRF's `namelist.input` file.

j. Using Digital Filter Initialization

Digital filter initialization (DFI) is a new option in V3. It is a way to remove initial model imbalance as, for example, measured by the surface pressure tendency. This might be important when one is interested in the 0 – 6 hour simulation/forecast. It runs a digital filter during a short model integration, backward and forward, and then start the forecast. In WRF implementation, this is all done in a single job. In the current release, DFI can only be used in a single domain run.

No special requirement for data preparation.

Start with namelist template `namelist.input.dfi`. This namelist file contains an extra namelist record for DFI: `&dfi_control`. Edit it to match your case configuration. For a typical application, the following options are used:

`dfi_opt` = 3
`dfi_nfilter` = 7 (filter option: Dolph)
`dfi_cutoff_seconds` = 3600 (should not be longer than the filter window)
For time specification, it typically needs to integrate backward for 0.5 to 1 hour, and integrate forward for half of the time.

If option `dfi_write_filtered_input` is set to true, a filtered wrfinput file, `wrfinput_initialized_d01`, will be produced.

In Version 3.2, a constant boundary condition option is introduced for DFI. To use it, set `constant_bc = 1` in `&bdy_control`

If a different time step is used for DFI, one may use `time_step_dfi` to set it.

k. Using sst_update option

The WRF model physics does not predict sea-surface temperature, vegetation fraction, albedo and sea ice. For long simulations, the model provides an alternative to read in the time-varying data and update these fields. In order to use this option, one must have access to time-varying SST and sea ice fields. Twelve monthly values vegetation fraction and albedo are available from the `geogrid` program. Once these fields are processed via WPS, one may activate the following options in namelist record `&time_control` before running program `real.exe` and `wrf.exe`:

`sst_update` = 1 in *&physics*
`io_form_auxinput4` = 2
`auxinput4_inname` = "wrflowinp_d<domain>" (created by `real.exe`)
`auxinput4_interval` = 360, 360, 360,
`io_form_auxinput4` = 2

l. Using Adaptive Time Stepping

Adaptive time stepping is a way to maximize the time step that the model can use while keeping the model numerically stable. The model time step is adjusted based on the domain-wide horizontal and vertical stability criterion. The following set of values would typically work well.

`use_adaptive_time_step` = .true.
`step_to_output_time` = .true. (but nested domains may still be writing output at the desired time. Try to use `adjust_output_times` = .true. to make up for this.)
`target_cfl` = 1.2, 1.2, 1.2,
`max_step_increase_pct` = 5, 51, 51, (a large percentage value for the nest allows the time step for the nest to have more freedom to adjust)
`starting_time_step` = use (-1 means 6*DX at start time)
`max_time_step` : use fixed values for all domains, e.g. 8*DX
`min_time_step` : use fixed values for all domains, e.g. 4*DX
`adaptation_domain`: which domain is driving the adaptive time step

Also see the description of these options in the list of namelist on page 5-35.

m. Output Time Series

There is an option to output time series from a model run. To active the option, a file called "`tslist`" must be present in the WRF run directory. The `tslist` file contains a list of locations defined by their latitude and longitude along with a short description and an abbreviation for each location. A sample file looks something like this:

```
#-----------------------------------------------#
# 24 characters for name | pfx |  LAT  |   LON  |
```

```
#-----------------------------------------------#
Cape Hallett                hallt -72.330  170.250
McMurdo Station             mcm   -77.851  166.713
```

The first three lines in the file are regarded as header information, and are ignored. Given a `tslist` file, for each location inside a model domain (either coarse or nested) a file containing time series variables at each model time step will be written with the name `pfx.d<domain>.TS`, where pfx is the specified prefix for the location in the tslist file. The maximum number of time series locations is controlled by the namelist variable `max_ts_locs` in namelist record `&domains`. The default value is 5. The time series output contains selected variables at the surface, including 2 m temperature, vapor mixing ratio, 10 m wind components, u and v, rotated to the earth coordinate, etc.. More information for time series output can be found in `WRFV3/run/README.tslist`.

n. Using IO Quilting

This option allows a few processors to be set alone to do output only. It can be useful and performance-friendly if the domain sizes are large, and/or the time taken to write a output time is getting significant when compared to the time taken to integrate the model in between the output times. There are two variables for setting the option:

`nio_tasks_per_group`: How many processors to use per IO group for IO quilting. Typically 1 or 2 processors should be sufficient for this purpose.
`nio_groups`: How many IO groups for IO. Default is 1.

Examples of namelist for various applications

A few physics options sets (plus model top and number of vertical levels) are provided here for reference. They may provide a good starting point for testing the model in your application. Also note that other factors will affect the outcome. For example, the domain setup, the distributions of vertical model levels, and input data.

a. 1 – 4 km grid distances, convection-permitting runs for 1- 3 days run (as used for NCAR spring real-time convection forecast over US):

```
mp_physics                          = 8,
ra_lw_physics                       = 1,
ra_sw_physics                       = 2,
radt                                = 10,
sf_sfclay_physics                   = 2,
sf_surface_physics                  = 2,
bl_pbl_physics                      = 2,
bldt                                = 0,
cu_physics                          = 0,
```

```
ptop_requested                      = 5000,
e_vert                              = 35,
```

b. 20 – 30 km grid distances, 1- 3 day runs (e.g., NCAR daily real-time runs over US):

```
mp_physics                          = 4,
ra_lw_physics                       = 1,
ra_sw_physics                       = 2,
radt                                = 10,
sf_sfclay_physics                   = 2,
sf_surface_physics                  = 2,
bl_pbl_physics                      = 2,
bldt                                = 0,
cu_physics                          = 5,
cudt                                = 0,

ptop_requested                      = 5000,
e_vert                              = 30,
```

c. Cold region 15 – 45 km grid sizes (e.g. used in NCAR's Antarctic Mesoscale Prediction System):

```
mp_physics                          = 4,
ra_lw_physics                       = 1,
ra_sw_physics                       = 2,
radt                                = 10,
sf_sfclay_physics                   = 2,
sf_surface_physics                  = 2,
bl_pbl_physics                      = 2,
bldt                                = 0,
cu_physics                          = 1,
cudt                                = 5,
fractional_seaice                   = 1,
seaice_threshold                    = 0.0,

ptop_requested                      = 1000,
e_vert                              = 44,
```

d. Hurricane applications (e.g. 12, 4 and 1.33 km nesting used by NCAR's real-time hurricane runs):

```
mp_physics                          = 8,
ra_lw_physics                       = 1,
ra_sw_physics                       = 2,
radt                                = 10,
sf_sfclay_physics                   = 1,
sf_surface_physics                  = 1,
```

```
bl_pbl_physics                      = 1,
bldt                                = 0,
cu_physics                          = 1,  (only on 12 km grid)
cudt                                = 5,
isftcflx                            = 2,

ptop_requested                      = 2000,
e_vert                              = 36,
```

e. Regional climate case at 10 – 30 km grid sizes (e.g. used in NCAR's regional climate runs):

```
mp_physics                          = 6,
ra_lw_physics                       = 3,
ra_sw_physics                       = 3,
radt                                = 30,
sf_sfclay_physics                   = 1,
sf_surface_physics                  = 2,
bl_pbl_physics                      = 1,
bldt                                = 0,
cu_physics                          = 1,
cudt                                = 5,
sst_update                          = 1,
tmn_update                          = 1,
sst_skin                            = 1,
bucket_mm                           = 100.0,
bucket_J                            = 1.e9,

ptop_requested                      = 1000,
e_vert                              = 51,

spec_bdy_width                      = 10,
spec_zone                           = 1,
relax_zone                          = 9,
spec_exp                            = 0.33,
```

Check Output

Once a model run is completed, it is a good practice to check a couple of things quickly.

If you have run the model on multiple processors using MPI, you should have a number of `rsl.out.*` and `rsl.error.*` files. Type '`tail rsl.out.0000`' to see if you get '`SUCCESS COMPLETE WRF`'. This is a good indication that the model has run successfully.

The namelist options are written to a separate file: `namelist.output`.

Check the output times written to `wrfout*` file by using netCDF command:

```
ncdump –v Times wrfout_d01_yyyy-mm-dd_hh:00:00
```

Take a look at either `rsl.out.0000` file or other standard out file. This file logs the times taken to compute for one model time step, and to write one history and restart output:

```
Timing for main: time 2006-01-21_23:55:00 on domain  2:    4.91110 elapsed seconds.
Timing for main: time 2006-01-21_23:56:00 on domain  2:    4.73350 elapsed seconds.
Timing for main: time 2006-01-21_23:57:00 on domain  2:    4.72360 elapsed seconds.
Timing for main: time 2006-01-21_23:57:00 on domain  1:   19.55880 elapsed seconds.
```

and

```
Timing for Writing wrfout_d02_2006-01-22_00:00:00 for domain 2: 1.17970 elapsed seconds.
Timing for main: time 2006-01-22_00:00:00 on domain 1: 27.66230 elapsed seconds.
Timing for Writing wrfout_d01_2006-01-22_00:00:00 for domain 1: 0.60250 elapsed seconds.
```

If the model did not run to completion, take a look at these standard output/error files too. If the model has become numerically unstable, it may have violated the CFL criterion (for numerical stability). Check whether this is true by typing the following:

`grep cfl rsl.error.*` or `grep cfl wrf.out`

you might see something like these:

```
5 points exceeded cfl=2 in domain            1 at time   4.200000
  MAX AT i,j,k:          123          48          3 cfl,w,d(eta)= 4.165821
21 points exceeded cfl=2 in domain            1 at time   4.200000
  MAX AT i,j,k:          123          49          4 cfl,w,d(eta)= 10.66290
```

When this happens, consider using namelist option w_damping, and/or reducing time step.

Trouble Shooting

If the model aborts very quickly, it is likely that either the computer memory is not large enough to run the specific configuration, or the input data have some serious problem. For the first problem, try to type '`unlimit`' or '`ulimit -s unlimited`' to see if more memory and/or stack size can be obtained.

For OpenMP (smpar-compiled code), the stack size needs to be set large, but not unlimited. Unlimited stack size may crash the computer.

To check if the input data is the problem, use ncview or other netCDF file browser.

Another frequent error seen is '`module_configure: initial_config: error reading namelist`'. This is an error message from the model complaining about errors and typos in the `namelist.input` file. Edit `namelist.input` file with

caution. If unsure, always start with an available template. A namelist record where the namelist read error occurs is provided in the V3 error message, and it should help with identifying the error.

Physics and Dynamics Options

Physics Options

WRF offers multiple physics options that can be combined in any way. The options typically range from simple and efficient to sophisticated and more computationally costly, and from newly developed schemes to well tried schemes such as those in current operational models.

The choices vary with each major WRF release, but here we will outline those available in WRF Version 3.

1. Microphysics (mp_physics)

a. Kessler scheme: A warm-rain (i.e. no ice) scheme used commonly in idealized cloud modeling studies (*mp_physics* = 1).

b. Lin et al. scheme: A sophisticated scheme that has ice, snow and graupel processes, suitable for real-data high-resolution simulations (2).

c. WRF Single-Moment 3-class scheme: A simple efficient scheme with ice and snow processes suitable for mesoscale grid sizes (3).

d. WRF Single-Moment 5-class scheme: A slightly more sophisticated version of (c) that allows for mixed-phase processes and super-cooled water (4).

e. Eta microphysics: The operational microphysics in NCEP models. A simple efficient scheme with diagnostic mixed-phase processes (5).

f. WRF Single-Moment 6-class scheme: A scheme with ice, snow and graupel processes suitable for high-resolution simulations (6).

g. Goddard microphysics scheme. A scheme with ice, snow and graupel processes suitable for high-resolution simulations (7). New in Version 3.0.

h. New Thompson et al. scheme: A new scheme with ice, snow and graupel processes suitable for high-resolution simulations (8). This adds rain number concentration and updates the scheme from the one in Version 3.0. New in Version 3.1.

i. Milbrandt-Yau Double-Moment 7-class scheme (9). This scheme includes separate categories for hail and graupel with double-moment cloud, rain, ice, snow, graupel and hail. New in Version 3.2.

j. Morrison double-moment scheme (10). Double-moment ice, snow, rain and graupel for cloud-resolving simulations. New in Version 3.0.

k. WRF Double-Moment 5-class scheme (14). This scheme has double-moment rain. Cloud and CCN for warm processes, but is otherwise like WSM5. New in Version 3.1.

l. WRF Double-Moment 6-class scheme (16). This scheme has double-moment rain. Cloud and CCN for warm processes, but is otherwise like WSM6. New in Version 3.1.

m. Thompson et al. (2007) scheme (98). This is the older Version 3.0 Thompson scheme that used to be option 8.

2.1 Longwave Radiation (ra_lw_physics)

a. RRTM scheme: Rapid Radiative Transfer Model. An accurate scheme using look-up tables for efficiency. Accounts for multiple bands, trace gases, and microphysics species (*ra_lw_physics* = 1).

b. GFDL scheme: Eta operational radiation scheme. An older multi-band scheme with carbon dioxide, ozone and microphysics effects (99).

c. CAM scheme: from the CAM 3 climate model used in CCSM. Allows for aerosols and trace gases (3).

d. RRTMG scheme. A new version of RRTM added in Version 3.1 (4). It includes the MCICA method of random cloud overlap.

2.2 Shortwave Radiation (ra_sw_physics)

a. Dudhia scheme: Simple downward integration allowing efficiently for clouds and clear-sky absorption and scattering (*ra_sw_physics* = 1).

b. Goddard shortwave: Two-stream multi-band scheme with ozone from climatology and cloud effects (2).

c. GFDL shortwave: Eta operational scheme. Two-stream multi-band scheme with ozone from climatology and cloud effects (99).

d. CAM scheme: from the CAM 3 climate model used in CCSM. Allows for aerosols and trace gases (3).

e. RRTMG shortwave. A new shortwave scheme with the MCICA method of random cloud overlap (4). New in Version 3.1.

f. Held-Suarez relaxation. A temperature relaxation scheme designed for idealized tests only (31).

g. Slope and shading effects. *slope_rad* = 1 modifies surface solar radiation flux according to terrain slope. *topo_shad* = 1 allows for shadowing of neighboring grid cells. Use only with high-resolution runs with grid size less than a few kilometers. Since Version 3.2, these are available for all shortwave options.

3.1 Surface Layer (sf_sfclay_physics)

a.MM5 similarity: Based on Monin-Obukhov with Carslon-Boland viscous sub-layer and standard similarity functions from look-up tables (*sf_sfclay_physics* = 1).

b. Eta similarity: Used in Eta model. Based on Monin-Obukhov with Zilitinkevich thermal roughness length and standard similarity functions from look-up tables(2).

c. Pleim-Xiu surface layer. (7). New in Version 3.0.

d. QNSE surface layer. Quasi-Normal Scale Elimination PBL scheme's surface layer option (4). New in Version 3.1.

e. MYNN surface layer. Nakanishi and Niino PBL's surface layer scheme (5). New in Version 3.1.

f. *iz0tlnd* = 1 (for *sf_sfclay_physics* = 1 or 2), Chen-Zhang thermal roughness length over land, which depends on vegetation height, 0 = original thermal roughness length in each sfclay option. New in Vserion 3.2.

3.2 Land Surface (sf_surface_physics)

a. 5-layer thermal diffusion: Soil temperature only scheme, using five layers (*sf_surface_physics* = 1).

b. Noah Land Surface Model: Unified NCEP/NCAR/AFWA scheme with soil temperature and moisture in four layers, fractional snow cover and frozen soil physics. New modifications are added in Version 3.1 to better represent processes over ice sheets and snow covered area.

c. RUC Land Surface Model: RUC operational scheme with soil temperature and moisture in six layers, multi-layer snow and frozen soil physics (3).

d. Pleim-Xiu Land Surface Model. Two-layer scheme with vegetation and sub-grid tiling (7). New in Version 3.0.

e. Fractional sea-ice (*fractional_seaice* = 1). Treat sea-ice as fractional field. Require fractional sea-ice as input data. Data sources may include those from GFS or the National Snow and Ice Data Center (http://nsidc.org/data/seaice/index.html). Use XICE for Vtable entry instead of SEAICE. This option works with *sf_sfclay_physics* = 1, 2, and *sf_surface_physics* = 2, 3 in the present release. New in Version 3.1.

3.3 Urban Surface (sf_urban_physics – replacing old switch ucmcall)

a. Urban canopy model (1): 3-category UCM option with surface effects for roofs, walls, and streets.

b. BEP (2). Building Environment Parameterization: Multi-layer urban canopy model that allows for buildings higher than the lowest model levels. Only works with Noah LSM and Boulac and MYJ PBL options. New in Version 3.1.

c. BEM (3). Building Energy Model. Adds to BEP, building energy budget with heating and cooling systems. Works with same options as BEP. New in Version 3.2.

4. Planetary Boundary layer (bl_pbl_physics)

a. Yonsei University scheme: Non-local-K scheme with explicit entrainment layer and parabolic K profile in unstable mixed layer (*bl_pbl_physics* = 1).

b. Mellor-Yamada-Janjic scheme: Eta operational scheme. One-dimensional prognostic turbulent kinetic energy scheme with local vertical mixing (2).

c. MRF scheme: Older version of (a) with implicit treatment of entrainment layer as part of non-local-K mixed layer (99).

d. ACM2 PBL: Asymmetric Convective Model with non-local upward mixing and local downward mixing (7). New in Version 3.0.

e. Quasi-Normal Scale Elimination PBL (4). A TKE-prediction option that uses a new theory for stably stratified regions. New in Version 3.1.

f. Mellor-Yamada Nakanishi and Niino Level 2.5 PBL (5). Predicts sub-grid TKE terms. New in Version 3.1.

g. Mellor-Yamada Nakanishi and Niino Level 3 PBL (6). Predicts TKE and other second-moment terms. New in Version 3.1.

h. BouLac PBL (8): Bougeault-Lacarrère PBL. A TKE-prediction option. New in Version 3.1. Designed for use with BEP urban model.

i. LES PBL: A large-eddy-simulation (LES) boundary layer is available in Version 3. For this, *bl_pbl_physic* = 0, *isfflx* = 1, and *sf_sfclay_physics* and *sf_surface_physics* are selected. This uses diffusion for vertical mixing and must use *diff_opt* = 2, and *km_opt* = 2 or 3, see below. Alternative idealized ways of running the LESPBL are chosen with *isfflx* = 0 or 2. New in Version 3.0.

5. Cumulus Parameterization (cu_physics)

a. Kain-Fritsch scheme: Deep and shallow convection sub-grid scheme using a mass flux approach with downdrafts and CAPE removal time scale (*cu_physics* = 1).

b. Betts-Miller-Janjic scheme. Operational Eta scheme. Column moist adjustment scheme relaxing towards a well-mixed profile (2).

c. Grell-Devenyi ensemble scheme: Multi-closure, multi-parameter, ensemble method with typically 144 sub-grid members (3).

d. Grell 3d ensemble cumulus scheme. Scheme for higher resolution domains allowing for subsidence in neighboring columns (5). New in Version 3.0.

e. Old Kain-Fritsch scheme: Deep convection scheme using a mass flux approach with downdrafts and CAPE removal time scale (99).

f. *ishallow*: shallow convection option. = 1, option on. Works together with Grell 3D scheme (*cu_physics* = 5)

6. Other physics options

a. Options to use for tropical storm and hurricane applications:

- *omlcall* = 1: Simple ocean mixed layer model (1): 1-D ocean mixed layer model following that of Pollard, Rhines and Thompson (1972). Two other namelist options are available to specify the initial mixed layer depth (although one may ingest real mixed layer depth data) (*oml_hml0*) and temperature lapse rate below the mixed layer (*oml_gamma*). Since V3.2, this option works with all *sf_surface_physics* options.

- *isftcflx*: Modify surface bulk drag (Donelan) and enthalpy coefficients to be more in line with recent research results of those for tropical storms and hurricanes. This option also includes dissipative heating term in heat flux. It is only available for *sf_sfclay_physics* = 1. There are two options for computing enthalpy coefficients:

isftcflx = 1: constant Z_{0q} (since V3.2) for heat and moisture; *isftcflx* = 2 Garratt formulation, slightly different forms for heat and moisture.

b. Other options for long simulations (new in Version 3.1):

- *tmn_update*: update deep soil temperature (1).

- *sst_skin*: calculate skin SST based on Zeng and Beljaars (2005) (1)

- *bucket_mm*: bucket reset value for water equivalent precipitation accumulations (value in mm, -1 = inactive).

- *bucket_J*: bucket reset value for energy accumulations (value in Joules, -1 = inactive). Only works with CAM and RRTMG radiation (*ra_lw_physics* = 3 and 4 and *ra_sw_physics* = 3 and 4) options.

- To drive WRF model with climate data that does not have leap year, there is a compile option to do that. Edit `configure.wrf` and add -DNO_LEAP_CALENDAR to the macro ARCH_LOCAL.

c. *usemonalb*: When set to .true., it uses monthly albedo fields from geogrid, instead of table values

d. *no_mp_heating*: When set to 1, it turns off latent heating from microphysics. When using this option, *cu_physics* should be set to 0.

e. *gwd_opt*: Gravity wave drag option. Can be activated when grid size is greater than 10 km. May be beneficial for simulations longer than 5 days and over a large domain with mountain ranges. New in Version 3.1.

Diffusion and Damping Options

Diffusion in WRF is categorized under two parameters, the diffusion option and the K option. The diffusion option selects how the derivatives used in diffusion are calculated, and the K option selects how the K coefficients are calculated. Note that when a PBL option is selected, vertical diffusion is done by the PBL scheme, and not by the diffusion scheme. In Version 3, vertical diffusion is also linked to the surface fluxes.

1.1 Diffusion Option (diff_opt)

a. Simple diffusion: Gradients are simply taken along coordinate surfaces (*diff_opt* = 1).

b. Full diffusion: Gradients use full metric terms to more accurately compute horizontal gradients in sloped coordinates (*diff_opt* = 2).

1.2 K Option (km_opt)

Note that when using a PBL scheme, only options (a) and (d) below make sense, because (b) and (c) are designed for 3d diffusion.

a. Constant: K is specified by namelist values for horizontal and vertical diffusion (*km_opt* = 1).

b. 3d TKE: A prognostic equation for turbulent kinetic energy is used, and K is based on TKE (*km_opt* = 2).

c. 3d Deformation: K is diagnosed from 3d deformation and stability following a Smagorinsky approach (*km_opt* = 3).

d. 2d Deformation: K for horizontal diffusion is diagnosed from just horizontal deformation. The vertical diffusion is assumed to be done by the PBL scheme (*km_opt* = 4).

1.3 6th Order Horizontal Diffusion (diff_6th_opt)

6^{th}-order horizontal hyper diffusion (del^6) on all variables to act as a selective short-wave numerical noise filter. Can be used in conjunction with *diff_opt*. = 1: simple; = 2: positive definite. Option 2 is recommended.

1.4 Nonlinear Backscatter Anisotropic (NBA) (sfs_opt)

Sub-grid turbulent stress option for momentum in LES applications. New in Version 3.2. *sfs_opt* = 1 diagnostic sub-grid stress to be used with *diff_opt* = 2 and *km_opt* = 2 or 3. *sfs_opt* = TKE sub-grid stress to be used with *diff_opt* = 2 and *km_opt* = 2.

2. Damping Options

These are independently activated choices.

a. Upper Damping: Either a layer of increased diffusion (*damp_opt* =1) or a Rayleigh relaxation layer (2) or an implicit gravity-wave damping layer (3, new in Version 3.0), can be added near the model top to control reflection from the upper boundary.

b. Vertical velocity damping (*w_damping*): For operational robustness, vertical motion can be damped to prevent the model from becoming unstable with locally large vertical velocities. This only affects strong updraft cores, so has very little impact on results otherwise.

c. Divergence Damping (*sm_div*): Controls horizontally propagating sound waves.

d. External Mode Damping (*em_div*): Controls upper-surface (external) waves.

e. Time Off-centering (*epssm*): Controls vertically propagating sound waves.

Advection Options

a. Horizontal advection orders for momentum (*h_mom_adv_order*) and scalar (*h_sca_adv_order*) can be $2^{nd}$to 6^{th}, with 5^{th} order being the recommended one.

b. Vertical advection orders for momentum (*v_mom_adv_order*) and scalar (v_sca_adv_order) can be $2^{nd}$and 6th, with 3^{rd} order being the recommended one.

c. Monotonic transport (option 2, new in Version 3.1) and positive-definite advection option (option 1) can be applied to moisture (*moist_adv_opt*), scalar (*scalar_adv_opt*), chemistry variables (*chem_adv_opt*) and tke (*tke_adv_opt*). Option 1 replaces *pd_moist* = .true. etc. in previous versions.

Some notes about using monotonic and positive-definite advection options:

The positive-definite and monotonic options are available for moisture, scalars, chemical scalers and TKE in the ARW solver. Both the monotonic and positive-definite transport options conserve scalar mass locally and globally and are consistent with the ARW mass conservation equation. We recommend using the positive-definite option for moisture variables on all real-data simulations. The monotonic option may be beneficial in chemistry applications and for moisture and scalars in some instances.

When using these options there are certain aspects of the ARW integration scheme that should be considered in the simulation configuration.

(1) The integration sequence in ARW changes when the positive-definite or monotonic options are used. When the options are not activated, the timestep tendencies from the physics (excluding microphysics) are used to update the scalar mixing ratio at the same time as the transport (advection), and the microphysics is computed and moisture is updated based on the transport+physics update. When the monotonic or positive definite options are activated, the scalar mixing ratio is first updated with the physics tendency, and the new updated values are used as the starting values for the transport scheme. The microphysics update occurs after the transport update using these latest values as its starting point. It is important to remember that for any scalars, the local and global conservation properties, positive definiteness and monotonicity depend upon each update possessing these properties.

(2) Some model filters may not be positive definite.

i. *diff_6th_opt* = 1 is not positive definite nor monotonic. Use *diff_6th_opt* = 2 if you need this diffusion option (*diff_6th_opt* = 2 is monotonic and positive-definite). We have encountered cases where the departures from monotonicity and positive-definiteness have been very noticeable.
ii. *diff_opt* = 1 and *km_opt* = 4 (a commonly-used real-data case mixing option) is not guaranteed to be positive-definite nor monotonic due to the variable eddy diffusivity K. We have not observed significant departures from positive-definiteness or monotonicity when this filter is used with these transport options.
iii. The diffusion option that uses a user-specified constant eddy viscosity is positive definite and monotonic.
iv. Other filter options that use variable eddy viscosity are not positive definite or monotonic.

(3) Most of the model physics are not monotonic nor should they be - they represent sources and sinks in the system. All should be positive definite, although we have not examined and tested all options for this property.

(4) The monotonic option adds significant smoothing to the transport in regions where it is active. You may want to consider turning off the other model filters for

variables using monotonic transport (filters such as the second and sixth order horizontal filters). At present it is not possible to turn off the filters for the scalars but not for the dynamics using the namelist - one must manually comment out the calls in the solver. In the next release we will make this capability available through the namelist.

Other Dynamics Options

a. The model can be run hydrostatically by setting *non_hydrostatic* switch to .false.

b. Coriolis term can be applied to wind perturbation (*pert_coriolis* = .true.) only (idealized only).

c. For *diff_opt* = 2 only, vertical diffusion may act on full fields (not just on perturbation from 1D base profile (*mix_full_fields* = .true.; idealized only).

Lateral Boundary Condition Options

a. Periodic (*periodic_x* / *periodic_y*): for idealized cases.

b. Open (*open_xs, open_xe, open_ys, open_ye*): for idealized cases.

c. Symmetric (*symmetric_xs, symmetric_xe, symmetric_ys, symmetric_ye*): for idealized cases.

d. Specified (*specified*): for real-data cases. The first row and column are specified with external model values (*spec_zone* = 1, and it should not change). The rows and columns in *relax_zone* have values blended from external model and WRF. The value of *relax_zone* may be changed, as long as *spec_bdy_width* = *spec_zone* + *relax_zone*. Can be used with *periodic_x* in tropical channel simulations.

   spec_exp: exponential multiplier for relaxation zone ramp, used with *specified* boundary condition. 0. = linear ramp, default; 0.33 = ~3*dx exp decay factor. May be useful for long simulations.

e. Nested (*nested*): for real and idealized cases.

Summary of PBL Physics Options

bl_pbl_physics	Scheme	Reference	Added
1	YSU	Hong, Noh and Dudhia (2006, MWR)	2004
2	MYJ	Janjic (1994, MWR)	2000
3	GFS	Hong and Pan (1996, MWR)	2005
4	QNSE	Sukoriansky, Galperin and Perov (2005, BLM)	2009
5	MYNN2	Nakanishi and Niino (2006, BLM)	2009
6	MYNN3	Nakanishi and Niino (2006, BLM)	2009

7	ACM2	Pleim (2007, JAMC	2008
8	BouLac	Bougeault and Lacarrere (1989, MWR)	2009
99	MRF	Hong and Pan (1996, MWR)	2000

bl_pbl_physics	Scheme	Cores	sf_sfclay_physics	Prognostic variables	Diagnostic variables	Cloud mixing
1	YSU	ARW/ NMM	1		exch_h	QC,QI
2	MYJ	ARW/ NMM	2	TKE_MYJ	EL_MYJ, exch_h	QC,QI
3	GFS (hwrf)	NMM	3			QC,QI
4	QNSE	ARW/ NMM	4	TKE_MYJ	EL_MYJ, exch_h, exch_m	QC,QI
5	MYNN2	ARW	1,2,5	QKE	Tsq, Qsq, Cov, exch_h, exch_m	QC
6	MYNN3	ARW	1,2,5	QKE, Tsq, Qsq, Cov	exch_h, exch_m	QC
7	ACM2	ARW	1,7			QC,QI
8	BouLac	ARW	1,2	TKE_PBL	EL_PBL, exch_h, exch_m, wu_tur, wv_tur, wt_tur, wq_tur	QC
99	MRF	ARW/ NMM	1			QC,QI

Summary of Microphysics Options

mp_physics	Scheme	Reference	Added
1	Kessler	Kessler (1969)	2000
2	Lin (Purdue)	Lin, Farley and Orville (1983, JCAM)	2000
3	WSM3	Hong, Dudhia and Chen (2004, MWR)	2004
4	WSM5	Hong, Dudhia and Chen (2004, MWR)	2004
5	Eta (Ferrier)	Rogers, Black, Ferrier, Lin, Parrish and DiMego (2001, web doc)	2000
6	WSM6	Hong and Lim (2006, JKMS)	2004
7	Goddard	Tao, Simpson and McCumber (1989, MWR)	2008
8 (+98)	Thompson (+old)	Thompson, Field, Rasmussen and Hall (2008, MWR)	2009
9	Milbrandt 2-mom	Milbrandt and Yau (2005, JAS)	2010
10	Morrison 2-mom	Hong and Pan (1996, MWR)	2008
14	WDM5	Lim and Hong (2010)	2009
16	WDM6	Lim and Hong (2010)	2009

mp_physics	Scheme	Cores	Mass Variables	Number Variables
1	Kessler	ARW	Qc Qr	
2	Lin (Purdue)	ARW	Qc Qr Qi Qs Qg	
3	WSM3	ARW	Qc Qr	
4	WSM5	ARW/NMM	Qc Qr Qi Qs	
5	Eta (Ferrier)	ARW/NMM	Qc Qr Qs (Qt*)	
6	WSM6	ARW/NMM	Qc Qr Qi Qs Qg	
7	Goddard	ARW	Qc Qr Qi Qs Qg	

8 (/98)	Thompson(/old)	ARW/NMM	Qc Qr Qi Qs Qg	Ni Nr (/Ni)
9	Milbrandt 2-mom	ARW	Qc Qr Qi Qs Qg Qh	Nc Nr Ni Ns Ng Nh
10	Morrison 2-mom	ARW	Qc Qr Qi Qs Qg	Nr Ni Ns Ng
14	WDM5	ARW	Qc Qr Qi Qs	Nn** Nc Nr
16	WDM6	ARW	Qc Qr Qi Qs Qg	Nn** Nc Nr

***** Advects only total condensates ** Nn = CCN number

Description of Namelist Variables

The following is a description of namelist variables. The variables that are a function of nests are indicated by *(max_dom)* following the variable. Also see `Registry/Registry.EM` and `run/README.namelist` file in WRFV3/ directory.

Variable Names	Value	Description
`&time_control`		Time control
`run_days`	1	run time in days
`run_hours`	0	run time in hours Note: if it is more than 1 day, one may use both run_days and run_hours or just run_hours. e.g. if the total run length is 36 hrs, you may set run_days = 1, and run_hours = 12, or run_days = 0, and run_hours 36
`run_minutes`	0	run time in minutes
`run_seconds`	0	run time in seconds
`start_year (max_dom)`	2001	four digit year of starting time
`start_month (max_dom)`	06	two digit month of starting time
`start_day (max_dom)`	11	two digit day of starting time
`start_hour (max_dom)`	12	two digit hour of starting time
`start_minute (max_dom)`	00	two digit minute of starting time
`start_second (max_dom)`	00	two digit second of starting time Note: the start time is used to name the first wrfout file. It also controls the start time for nest domains, and the time to restart
`end_year (max_dom)`	2001	four digit year of ending time

end_month (max_dom)	06	two digit month of ending time
end_day (max_dom)	12	two digit day of ending time
end_hour (max_dom)	12	two digit hour of ending time
end_minute (max_dom)	00	two digit minute of ending time
end_second (max_dom)	00	two digit second of ending time Note all end times also control when the nest domain integrations end. All start and end times are used by *real.exe*. One may use either run_days/run_hours etc. or end_year/month/day/hour etc. to control the length of model integration. But run_days/run_hours takes precedence over the end times. Program *real.exe* uses start and end times only.
interval_seconds	10800	time interval between incoming real data, which will be the interval between the lateral boundary condition file (for *real* only)
input_from_file (max_dom)	T (logical)	logical; whether nested run will have input files for domains other than 1
fine_input_stream (max_dom)		selected fields from nest input
	0	all fields from nest input are used
	2	only nest input specified from input stream 2 (defined in the Registry) are used. In V3.2, this requires io_form_auxinput2 to be set
history_interval (max_dom)	60	history output file interval in minutes (integer only)
history_interval_d (max_dom)	1	history output file interval in days (integer); used as alternative to history_interval
history_interval_h (max_dom)	1	history output file interval in hours (integer); used as alternative to history_interval
history_interval_m (max_dom)	1	history output file interval in minutes (integer); used as alternative to history_interval and is equivalent to history_interval
history_interval_s (max_dom)	1	history output file interval in seconds (integer); used as alternative to history_interval
frames_per_outfile (max_dom)	1	output times per history output file, used to

		split output files into smaller pieces
restart	F (logical)	whether this run is a restart run
restart_interval	1440	restart output file interval in minutes
reset_simulation_start	F	whether to overwrite simulation_start_date with forecast start time
cycling	F	whether this run is a cycling run (initialized from wrfout file)
auxinput1_inname	“met_em.d<domain> <date>”	input from WPS (this is the default)
auxinput4_inname	“wrflowinp_d<domain>”	input for lower bdy file, works with sst_update = 1
auxinput4_interval (max_dom)	360	file interval in minutes for lower boundary file
io_form_auxinput4	2	IO format for wrflowinp files, required for V3.2
io_form_history	2	2 = netCDF; 102 = split netCDF files one per processor (no supported post-processing software for split files)
	1	binary format (no supported post-processing software avail)
	4	PHDF5 format (no supported post-processing software avail)
	5	GRIB 1
	10	GRIB 2
	11	parallel netCDF
io_form_restart	2	2 = netCDF; 102 = split netCDF files one per processor (must restart with the same number of processors)
io_form_input	2	2 = netCDF
	102	allows program real.exe to read in split met_em* files, and write split wrfinput files. No split file for wrfbdy.
io_form_boundary	2	netCDF format
io_form_auxinput4	2	IO format (netCDF) for wrflowinp
io_form_auxinput2	2	IO format (netCDF) for input stream 2 data
cycling	.false.	indicating if the run is using wrfout file as input file. In this case, Thompson initialization routine will not be called again (performance issue)
diag_print	0	getting some simple diagnostic fields

	1	domain averaged Dpsfc/Dt, Dmu/Dt will appear in stdout file
	2	in addition to those above, domain averaged rainfall, surface evaporation, sensible and latent heat fluxes will be output
debug_level	0	50,100,200,300 values give increasing prints
auxhist2_outname	"rainfall_d<domain>"	file name for extra output; if not specified, auxhist2_d<domain>_<date> will be used. Also note that to write variables in output other than the history file requires Registry.EM file change
auxhist2_interval (max_dom)	10	interval in minutes
io_form_auxhist2	2	output in netCDF
frame_per_auxhist2 (max_dom)		output times per output file
auxinput11_interval		designated for obs nudging input
auxinput11_end_h		designated for obs nudging input
nocolons	.false.	replace : with _ in output file names
write_input	t	write input-formatted data as output for 3DVAR application
inputout_interval	180	interval in minutes when writing input-formatted data
input_outname	“wrf_3dvar_input_ d<domain>_<date>”	Output file name from 3DVAR
inputout_begin_y	0	beginning year to write 3DVAR data
inputout_begin_d	0	beginning day to write 3DVAR data
inputout_begin_h	3	beginning hour to write 3DVAR data
Inputout_begin_m	0	beginning minute to write 3DVAR data
inputout_begin_s	0	beginning second to write 3DVAR data
inputout_end_y	0	ending year to write 3DVAR data
inputout_end_d	0	ending day to write 3DVAR data
inputout_end_h	12	ending hour to write 3DVAR data
inputout_end_m	0	ending minute to write 3DVAR data
inputout_end_s	0	ending second to write 3DVAR data. The above example shows that the input-formatted data are output starting from hour 3 to hour 12 in 180 min interval.
all_ic_times	1	output wrfinput file for all time periods

&domains		domain definition: dimensions, nesting parameters
time_step	60	time step for integration in integer seconds (recommended 6*dx in km for a typical case)
time_step_fract_num	0	numerator for fractional time step
time_step_fract_den	1	denominator for fractional time step Example, if you want to use 60.3 sec as your time step, set time_step = 60, time_step_fract_num = 3, and time_step_fract_den = 10
time_step_dfi	60	time step for DFI, may be different from regular time_step
max_dom	1	number of domains - set it to > 1 if it is a nested run
s_we (max_dom)	1	start index in x (west-east) direction (leave as is)
e_we (max_dom)	91	end index in x (west-east) direction (staggered dimension)
s_sn (max_dom)	1	start index in y (south-north) direction (leave as is)
e_sn (max_dom)	82	end index in y (south-north) direction (staggered dimension)
s_vert (max_dom)	1	start index in z (vertical) direction (leave as is)
e_vert (max_dom)	28	end index in z (vertical) direction (staggered dimension - this refers to full levels). Most variables are on unstaggered levels. Vertical dimensions need to be the same for all nests.
dx (max_dom)	10000	grid length in x direction, unit in meters
dy (max_dom)	10000	grid length in y direction, unit in meters
ztop (max_dom)	19000.	height in meters; used to define model top for idealized cases
grid_id (max_dom)	1	domain identifier
parent_id (max_dom)	0	id of the parent domain
i_parent_start (max_dom)	1	starting LLC I-indices from the parent domain
j_parent_start (max_dom)	1	starting LLC J-indices from the parent domain
parent_grid_ratio (max_dom)	1	parent-to-nest domain grid size ratio: for real-data cases the ratio has to be odd; for

		idealized cases, the ratio can be even if feedback is set to 0.
parent_time_step_ratio (max_dom)	1	parent-to-nest time step ratio; it can be different from the parent_grid_ratio
feedback	1	feedback from nest to its parent domain; 0 = no feedback
smooth_option	0	smoothing option for parent domain, used only with feedback option on. 0: no smoothing; 1: 1-2-1 smoothing; 2: smoothing-desmoothing

(options for program real)

num_metgrid_levels	40	number of vertical levels in WPS output: type `ncdump -h` to find out
num_metgrid_soil_ levels	4	number of soil levels or layers in WPS output
eta_levels	1.0, 0.99,…0.0	model *eta* levels from 1 to 0. If not given, *real* will provide a set of levels
force_sfc_in_vinterp	1	use surface data as lower boundary when interpolating through this many eta levels
p_top_requested	5000	p_top to use in the model; must be available in WPS data
interp_type	2	vertical interpolation; 1: linear in pressure; 2: linear in log(pressure)
extrap_type	2	vertical extrapolation of non-temperature variables. 1: extrapolate using the two lowest levels; 2: use lowest level as constant below ground
t_extrap_type	2	vertical extrapolation for potential temperature. 1: isothermal; 2: -6.5 K/km lapse rate for temperature 3: constant theta
use_levels_below_groun d	.true.	in vertical interpolation, whether to use levels below input surface level: true: use input isobaric levels below input surface false: extrapolate when WRF location is below input surface level
use_surface	.true.	whether to use input surface level data in vertical interpolation true: use input surface data

		false: do not use input surface data
lagrange_order	1	vertical interpolation order; 1: linear; 2: quadratic
lowest_lev_from_sfc	.false.	T = use surface values for the lowest *eta* (u,v,t,q); F = use traditional interpolation
sfcp_to_sfcp	.false.	optional method to compute model's surface pressure when incoming data only has surface pressure and terrain, but not SLP
use_tavg_for_tsk	.false.	whether to use diurnally averaged surface temp as skin temp. The diurnall averaged surface temp can be computed using WPS utility `avg_tsfc.exe`. May use this option when SKINTEMP is not present.
rh2qv_wrt_liquid	.true.	whether to compute Qv with respect to water (true) or ice (false)
smooth_cg_topo	.false.	smooth the outer rows and columns of the domain 1 topography w.r.t. the input data
use_tavg_for_tsk	.false.	whether to use diurnally averaged surface temp as skin temp. The diurnall averaged surface temp can be computed using WPS utility `avg_tsfc.exe`. May use this option when SKINTEMP is not present
vert_refine_fact	1	vertical refinement factor for `ndown`
(options for preset moving nest)		
num_moves	2,	total number of moves for all domains
move_id (max_moves)	2,2,	a list of nest domain id's, one per move
move_interval (max_moves)	60,120,	time in minutes since the start of this domain
move_cd_x (max_moves)	1,-1,	the number of parent domain grid cells to move in i direction
move_cd_y (max_moves)	-1,1,	the number of parent domain grid cells to move in j direction (positive in increasing i/j directions, and negative in decreasing i/j directions. Only 1, 0 and -1 is permitted.
(options for automatic moving nest)		
vortex_interval (max_dom)	15	how often the new vortex position is computed
max_vortex_speed (max_dom)	40	unit in m/sec; used to compute the search radius for the new vortex position
corral_dist (max_dom)	8	how many coarse grid cells the moving

		nest is allowed to get near the coarse grid boundary
track_level	50000.	Pressure level value (Pa) at which the tropical storm vortex is tracked
time_to_move (max_dom)	0.,	time, in minutes, to start moving nest
(options for adaptive time step)		
use_adaptive_time_step	.false.	whether to use adaptive time step
step_to_output_time	.true.	whether to modify the time steps so that the exact history time is reached
target_cfl(max_dom)	1.2. 1.2, 1.2,	if vertical and horizontal CFL <= this value, then time step is increased
max_step_increase_pct(max_dom)	5, 51, 51,	percentage of previous time step to increase, if the max CFL is <= target_cfl
starting_time_step (max_dom)	-1, -1, -1,	flag -1 implies 6*dx is used to start the model. Any positive integer number specifies the time step the model will start with. Note that when use_adaptive_time_step is true, the value specified for time_step is ignored.
max_time_step(max_dom)	-1, -1, -1,	flag -1 implies the maximum time step is 3*starting_time_step. Any positive integer number specified the maximum time step
min_time_step (max_dom)	-1, -1, -1,	flag -1 implies the minimum time step is 0.5*starting_time_step. Any positive integer number specified the minumum time step
adaptation_domain	1	Which domain to drive adaptive time stepping. Default is domain 1.
(options to control parallel computing)		
tile_sz_x	0	number of points in tile x direction
tile_sz_y	0	number of points in tile y direction can be determined automatically
numtiles	1	number of tiles per patch (alternative to above two items)
nproc_x	-1	number of processors in x for decomposition
nproc_y	-1	number of processors in y for decomposition -1: code will do automatic decomposition >1: for both: will be used for

		decomposition
&physics		Physics options
mp_physics (max_dom)		*microphysics option*
	0	no microphysics
	1	Kessler scheme
	2	Lin et al. scheme
	3	WSM 3-class simple ice scheme
	4	WSM 5-class scheme
	5	Ferrier (new Eta) microphysics
	6	WSM 6-class graupel scheme
	7	Goddard GCE scheme (also use gsfcgce_hail and gsfcgce_2ice)
	8	Thompson graupel scheme (2-moment scheme in V3.1)
	9	Milbrandt-Yau 2-moment scheme
	10	Morrison 2-moment scheme
	14	double moment, 5-class scheme
	16	double moment, 6-class scheme
	98	Thompson scheme in V3.0
mp_zero_out		For non-zero mp_physics options, this keeps moisture variables above a threshold value >= 0. An alternative (and better) way to keep moisture variables positive is to use moist_adv_opt.
	0	no action taken, no adjustment to any moisture field
	1	except for Qv, all other moisture arrays are set to zero if they fall below a critical value
	2	Qv >= 0 and all other moisture arrays are set to zero if they fall below a critical value
mp_zero_out_thresh	1.e-8	critical value for moisture variable threshold, below which moisture arrays (except for Qv) are set to zero (unit: kg/kg)
mp_tend_lim	10..	limit on temp tendency from microphysics latent heating when radar data assimilation is used
gsfcgce_hail	0	0: running gsfcgce scheme with graupel 1: running gsfcgce scheme with hail
gsfcgce_2ice	0	0: running gsfcgce scheme with snow, ice

		and graupel / hail 1: running gsfcgce scheme with only ice and snow 2: running gsfcgce scheme with only ice and graupel (used only in very extreme situation)
`no_mp_heating`	0	switch to turn off latent heating from mp 0: normal 1: turn off latent heating from a microphysics scheme
`ra_lw_physics (max_dom)`		longwave radiation option
	0	no longwave radiation
	1	rrtm scheme
	3	CAM scheme
	4	rrtmg scheme
	99	GFDL (Eta) longwave (semi-supported)
`ra_sw_physics (max_dom)`		shortwave radiation option
	0	no shortwave radiation
	1	Dudhia scheme
	2	Goddard short wave
	3	CAM scheme
	4	rrtmg scheme
	99	GFDL (Eta) longwave (semi-supported)
`radt (max_dom)`	30	minutes between radiation physics calls. Recommend 1 minute per km of dx (e.g. 10 for 10 km grid); use the same value for all nests
`co2tf`	1	CO2 transmission function flag for GFDL radiation only. Set it to 1 for ARW, which allows generation of CO2 function internally
`cam_abs_freq_s`	21600	CAM clear sky longwave absorption calculation frequency (recommended minimum value to speed scheme up)
`levsiz`	59	for CAM radiation input ozone levels
`paerlev`	29	for CAM radiation input aerosol levels
`cam_abs_dim1`	4	for CAM absorption save array
`cam_abs_dim2`	same as e_vert	for CAM 2nd absorption save array. The above 5 variables for CAM are automatically set in V3.2.

`sf_sfclay_physics (max_dom)`		surface-layer option
	0	no surface-layer
	1	Monin-Obukhov scheme
	2	Monin-Obukhov (Janjic Eta) scheme
	3	NCEP GFS scheme (NMM only)
	4	QNSE
	5	MYNN
	7	Pleim-Xiu (ARW only), only tested with Pleim-Xiu surface and ACM2 PBL
`iz0tlnd`	0	thermal roughness length for sfclay and myjsfc (0 - old, 1 - veg dependent Czil)
`sf_surface_physics (max_dom)`		land-surface option (set before running *real*; also set correct `num_soil_layers`)
	0	no surface temp prediction
	1	thermal diffusion scheme
	2	unified Noah land-surface model
	3	RUC land-surface model
	7	Pleim-Xiu scheme (ARW only)
`sf_urban_physics (max_dom)`		urban physics option (replacing `ucmcall` option in previous versions); works with Noah LSM
	0	no urban physics
	1	single-layer UCM (Kusaka)
	2	multi-layer, BEP (Martilli); works with BouLac and MYJ PBL only.
`bl_pbl_physics (max_dom)`		boundary-layer option
	0	no boundary-layer
	1	YSU scheme, use sf_sfclay_physics=1
	2	Mellor-Yamada-Janjic (Eta) TKE scheme, use `sf_sfclay_physics`=2
	3	NCEP GFS scheme (NMM only), use `sf_sfclay_physics`=3
	4	QNSE, use `sf_sfclay_physics`=4
	5	MYNN 2.5 level TKE, use `sf_sfclay_physics`=1,2, and 5
	6	MYNN 3rd level TKE, use `sf_sfclay_physics`=5
	7	ACM2 (Pleim) scheme, use `sf_sfclay_physics`=1, 7

	8	Bougeault and Lacarrere (BouLac) TKE, use `sf_sfclay_physics`=1, 2
	99	MRF scheme (to be removed)
`bldt (max_dom)`	0	minutes between boundary-layer physics calls. 0 = call every time step
`grav_settling (max_dom)`	0	Gravitational settling of fog/cloud droplet, MYNN PBL only
`cu_physics (max_dom)`		cumulus option
	0	no cumulus
	1	Kain-Fritsch (new Eta) scheme
	2	Betts-Miller-Janjic scheme
	3	Grell-Devenyi ensemble scheme
	4	Simplied Arakawa-Schubert (NMM only)
	5	New Grell scheme (G3)
	99	previous Kain-Fritsch scheme
`cudt`	0	minutes between cumulus physics calls. 0 = call every time step
`ishallow`	0	Shallow convection used with Grell 3D
`maxiens`	1	Grell-Devenyi and G3 only
`maxens`	3	G-D only
`maxens2`	3	G-D only
`maxens3`	16	G-D only
`ensdim`	144	G-D only. These are recommended numbers. If you would like to use any other number, consult the code, know what you are doing.
`cugd_avedx`	1	number of grid boxes over which subsidence is spread. 1= default, for large grid sizes; 3=, for small grid sizes (<5km)
`isfflx`	1	heat and moisture fluxes from the surface 1 = with fluxes from the surface 0 = no flux from the surface (not for `sf_surface_sfclay` = 2). If `diff_opt`=2, `km_opt`=2 or 3 then 0 = constant fluxes defind by `tke_drag_coefficient`, `tke_heat_flux`; 1 = use model computed u*, and heat and moisture fluxes; 2 = use model computed u*, and specified heat flux by `tke_heat_flux`
`ifsnow`	0	snow-cover effects (only works for

		sf_surface_physics = 1) 1 = with snow-cover effect 0 = without snow-cover effect
icloud	1	cloud effect to the optical depth in radiation (only works for ra_sw_physics = 1 and ra_lw_physics = 1) 1 = with cloud effect 0 = without cloud effect
swrad_scat	1.	Scattering tuning parameter (default 1 is 1.e-5 m^2/kg)
surface_input_source	1,2,3	where landuse and soil category data come from: 1 = WPS/geogrid, but with dominant categories recomputed in real 2 = GRIB data from another model (only if arrays VEGCAT/SOILCAT exist) 3 = use dominant land and soil categories from WPS/geogrid
num_soil_layers		number of soil layers in land surface model (set in *real*)
	5	thermal diffusion scheme for temp only
	4	Noah land-surface model
	6	RUC land-surface model
	2	Pleim-Xu land-surface model
pxlsm_smois_init (max_dom)	1	PX LSM soil moisture initialization option 0: from analysis 1: from LANDUSE.TBL (SLMO)
num_land_cat	24	number of landuse categories in input data
num_soil_cat	16	number of soil categories in input data
usemonalb	.false.	whether to use monthly albedo map instead of table values. Recommended for sst_update = 1
rdmaxalb	.true.	use snow albedo from geogrid; false means use snow albedo from table
rdlai2d	.false.	use LAI from input data; false means using values from table
seaice_threshold	271.	tsk < seaice_threshold, if water point and 5-layer slab scheme, set to land point and permanent ice; if water point and Noah scheme, set to land point, permanent ice, set temps from 3 m to surface, and set smois and sh2o
sst_update		option to use time-varying SST, seaice,

		vegetation fraction, and albedo during a model simulation (set before running *real*)
	0	no SST update
	1	*real.exe* will create `wrflowinp` file(s) at the same time interval as the available input data. Also set `auxinput4_inname = "wrflowinp_d<domain>"`, `auxinput4_interval` and `io_form_auxinput4` (required in V3.2) in namelist section *&time_control*
`tmn_update`	1	update deep layer soil temperature, useful for long simulations
`lagday`	150	days over which tmn is computed using skin temperature
`sst_skin`	1	calculate skin SST, useful for long simulations
`bucket_mm`	-1.	bucket reset values for water accumulation (unit in mm), useful for long simulations; -1 = inactive
`bucket_j`	-1.	bucket reset value for energy accumulations (unit in Joules) useful for long simulations; -1 = inactive
`slope_rad (max_dom)`	0	slope effects for `ra_sw_physics` (1=on, 0=off)
`topo_shading (max_dom)`	0	neighboring-point shadow effects for `ra_sw_physics` (1=on, 0=off)
`shadlen`	25000.	max shadow length in meters for `topo_shading = 1`
`omlcall`	0	simple ocean mixed layer model (1=on, 0=off)
`oml_hml0`	50.	>= 0: initial ocean mixed layer depth (m), constant everywhere < 0: use input
`oml_gamma`	0.14	lapse rate in deep water for oml (K m-1)
`isftcflx`	0	alternative Ck, Cd for tropical storm application. (0=off, 1=constant Z_{0q}, 2=Garratt)
`fractional_seaice`	0.	treat seaice as fractional field (1) or ice/no ice flag (0)
`prec_acc_dt`	0.	number of minutes in precipitation bucket if set greater than 0.

&fdda		*for grid, obs and spectral nudging*
(for grid nudging)		
grid_fdda (max_dom)	1	grid analysis nudging on (=0 off)
	2	spectral analysis nudging option
gfdda_inname	“wrffdda_d<domain>”	defined name in real
gfdda_interval (max_dom)	360	Time interval (min) between analysis times
gfdda_end_h (max_dom)	6	Time (h) to stop nudging after start of forecast
io_form_gfdda	2	analysis format (2 = netcdf)
fgdt (max_dom)	0	calculation frequency (in minutes) for analysis nudging. 0 = every time step, and this is recommended
fgdtzero	0	not active
	1	nudging tendencies are set to zero in between fdda calls
if_no_pbl_nudging_uv (max_dom)	0	1= no nudging of u and v in the pbl; 0= nudging in the pbl
if_no_pbl_nudging_t (max_dom)	0	1= no nudging of temp in the pbl; 0= nudging in the pbl
if_no_pbl_nudging_q (max_dom)	0	1= no nudging of qvapor in the pbl; 0= nudging in the pbl
if_no_pbl_nudging_ph (max_dom)	0	1= no nudging of ph in the pbl; 0= nudging in the pbl; only for spectral nudging
if_zfac_uv (max_dom)	0	0= nudge u and v in all layers, 1= limit nudging to levels above k_zfac_uv
k_zfac_uv	10	10=model level below which nudging is switched off for u and v
if_zfac_t (max_dom)	0	0= nudge temp in all layers, 1= limit nudging to levels above k_zfac_t
k_zfac_t	10	10=model level below which nudging is switched off for temp
if_zfac_q (max_dom)	0	0= nudge qvapor in all layers, 1= limit nudging to levels above k_zfac_q
k_zfac_q	10	10=model level below which nudging is switched off for water qvapor
if_zfac_ph (max_dom)	0	0= nudge ph in all layers, 1= limit nudging to levels above k_zfac_ph (spectral nudging only)

k_zfac_q	10	10=model level below which nudging is switched off for water ph (spectral nudging only)
guv (max_dom)	0.0003	nudging coefficient for u and v (sec-1)
gt (max_dom)	0.0003	nudging coefficient for temp (sec-1)
gq (max_dom)	0.0003	nudging coefficient for qvapor (sec-1)
gph (max_dom)	0.0003	nudging coefficient for ph (sec-1), spectral nudging only
dk_zfac_uv (max_dom)	1	depth in k between k_zfac_X to dk_zfac_X where nudging increases linearly to full strength (spectral nudging only)
dk_zfac_t (max_dom)	1	
dk_zfac_ph (max_dom)	1	
xwavenum	3	top wave number to nudge in x direction, spectral nudging only
ywavenum	3	top wave number to nudge in y direction, spectral nudging only
if_ramping	0	0= nudging ends as a step function, 1= ramping nudging down at end of period
dtramp_min	60.	time (min) for ramping function, 60.0=ramping starts at last analysis time, -60.0=ramping ends at last analysis time
grid_sfdda (max_dom)	1	surface grid-nudging on (=0 off)
sgfdda_inname	“wrfsfdda_d<domain>”	defined name for surface nudging input file (from program obsgrid)
sgfdda_interval (max_dom)	360	time interval (min) between surface analysis times
sgfdda_end_h (max_dom)	6	time (in hours) to stop nudging after start of forecast
io_form_sgfdda	2	surface analysis format (2 = netcdf)
guv_sfc (max_dom)	0.0003	nudging coefficient for u and v (sec-1)
gt_sfc (max_dom)	0.0003	nudging coefficient for temp (sec-1)
gq_sfc (max_dom)	0.0003	nudging coefficient for qvapor (sec-1)
rinblw	250.	radius of influence used to determine the confidence (or weights) for the analysis, which is based on the distance between the grid point to the nearest obs. The analysis without nearby observation is used at a reduced weight

(for obs nudging)

obs_nudge_opt (max_dom)	1	obs-nudging fdda on (=0 off) for each domain; also need to set auxinput11_interval and auxinput11_end_h in time_control namelist
max_obs	150000	max number of observations used on a domain during any given time window
fdda_startj(max_dom)	0.	obs nudging start time in minutes
fdda_end (max_dom)	180.	obs nudging end time in minutes
obs_nudge_wind (max_dom)	1	whether to nudge wind: (=0 off)
obs_coef_wind (max_dom)	6.e-4	nudging coefficient for wind, unit: s-1
obs_nudge_temp (max_dom)	1	whether to nudge temperature: (=0 off)
obs_coef_temp (max_dom)	6.e-4	nudging coefficient for temp, unit: s-1
obs_nudge_mois (max_dom)	1	whether to nudge water vapor mixing ratio: (=0 off)
obs_coef_mois (max_dom)	6.e-4	nudging coefficient for water vapor mixing ratio, unit: s-1
obs_nudge_pstr (max_dom)	0	whether to nudge surface pressure (not used)
obs_coef_pstr (max_dom)	0.	nudging coefficient for surface pressure, unit: s-1 (not used)
obs_rinxy	200.	horizontal radius of influence in km
obs_rinsig	0.1	vertical radius of influence in *eta*
obs_twindo (max_dom)	0.666667	half-period time window over which an observation will be used for nudging; the unit is in hours
obs_npfi	10	freq in coarse grid timesteps for diag prints
obs_ionf (max_dom)	2	freq in coarse grid timesteps for obs input and err calc
obs_idynin	0	for dynamic initialization using a ramp-down function to gradually turn off the FDDA before the pure forecast (=1 on)
obs_dtramp	40.	time period in minutes over which the nudging is ramped down from one to zero.
obs_prt_max	10	maximum allowed obs entries in diagnostic printout
obs_prt_freq (max_dom)	10	frequency in obs index for diagnostic printout

obs_ipf_in4dob	.true.	print obs input diagnostics (=.false. off)
obs_ipf_errob	.true.	print obs error diagnostics (=.false. off)
obs_ipf_nudob	.true.	print obs nudge diagnostics (=.false. off)
obs_ipf_init	.true.	enable obs init warning messages
obs_no_pbl_nudge_uv (max_dom)	0	1= no wind-nudging within pbl
obs_no_pbl_nudge_t (max_dom)	0	1= no temperature-nudging within pbl
obs_no_pbl_nudge_q (max_dom)	0	1= no moisture-nudging within pbl
obs_nudgezfullr1_uv	50	Vert infl full weight height for LML obs, regime 1, winds
obs_nudgezrampr1_uv	50	Vert infl ramp-to-zero height for LML obs, regime 1, winds
obs_nudgezfullr2_uv	50	Vert infl full weight height for LML obs, regime 2, winds
obs_nudgezrampr2_uv	50	Vert infl ramp-to-zero height for LML obs, regime 2, winds
obs_nudgezfullr4_uv	-5000	Vert infl full weight height for LML obs, regime 4, winds
obs_nudgezrampr4_uv	50	Vert infl ramp-to-zero height for LML obs, regime 4, winds
obs_nudgezfullr1_t	50	Vert infl full weight height for LML obs, regime 1, temperature
obs_nudgezrampr1_t	50	Vert infl ramp-to-zero height for LML obs, regime 1, temperature
obs_nudgezfullr2_t	50	Vert infl full weight height for LML obs, regime 2, temperature
obs_nudgezrampr2_t	50	Vert infl ramp-to-zero height for LML obs, regime 2, temperature
obs_nudgezfullr4_t	-5000	Vert infl full weight height for LML obs, regime 4, temperature
obs_nudgezrampr4_t	50	Vert infl ramp-to-zero height for LML obs, regime 4, temperature
obs_nudgezfullr1_q	50	Vert infl full weight height for LML obs, regime 1, moisture
obs_nudgezrampr1_q	50	Vert infl ramp-to-zero height for LML obs, regime 1, moisture
obs_nudgezfullr2_q	50	Vert infl full weight height for LML obs, regime 2, moisture
obs_nudgezrampr2_q	50	Vert infl ramp-to-zero height for LML obs, regime 2, moisture

obs_nudgezfullr4_q	-50000	Vert infl full weight height for LML obs, regime 4, moisture
obs_nudgezrampr4_q	50	Vert infl ramp-to-zero height for LML obs, regime 4, moisture
obs_nudgezfullmin	50	Min depth through which vertical infl fcn remains 1.0
obs_nudgezrampmin	50	Min depth (m) through which vert infl fcn decreases from 1 to 0
obs_nudgezmax	3000	Max depth (m) in which vert infl function is nonzero
obs_sfcfact	1.0	Scale factor applied to time window for surface obs
obs_sfcfacr	1.0	Scale factor applied to horiz radius of influence for surface obs
obs_dpsmx	7.5	Max pressure change (cb) allowed within horiz radius of influence

&dynamics *Diffusion, damping options, advection options*

rk_ord		time-integration scheme option:
	2	Runge-Kutta 2nd order
	3	Runge-Kutta 3rd order (recommended)
diff_opt		turbulence and mixing option:
	0	= no turbulence or explicit spatial numerical filters (km_opt IS IGNORED).
	1	evaluates 2nd order diffusion term on coordinate surfaces. uses kvdif for vertical diff unless PBL option is used. may be used with km_opt = 1 and 4. (= 1, recommended for real-data case)
	2	evaluates mixing terms in physical space (stress form) (x,y,z). turbulence parameterization is chosen by specifying km_opt.
km_opt		eddy coefficient option
	1	constant (use khdif and kvdif)
	2	1.5 order TKE closure (3D)
	3	Smagorinsky first order closure (3D) Note: option 2 and 3 are not recommended for DX > 2 km
	4	horizontal Smagorinsky first order closure (recommended for real-data case)

diff_6th_opt (max_dom)	0	6th-order numerical diffusion 0 = no 6th-order diffusion (default) 1 = 6th-order numerical diffusion 2 = 6th-order numerical diffusion but prohibit up-gradient diffusion
diff_6th_factor (max_dom)	0.12	6th-order numerical diffusion non-dimensional rate (max value 1.0 corresponds to complete removal of 2dx wave in one timestep)
damp_opt		upper level damping flag
	0	without damping
	1	with diffusive damping; maybe used for real-data cases (dampcoef nondimensional ~ 0.01 - 0.1)
	2	with Rayleigh damping (dampcoef inverse time scale [1/s], e.g. 0.003)
	3	with w-Rayleigh damping (dampcoef inverse time scale [1/s] e.g. 0.2; for real-data cases)
zdamp (max_dom)	5000	damping depth (m) from model top
dampcoef (max_dom)	0.	damping coefficient (see damp_opt)
w_damping		vertical velocity damping flag (for operational use)
	0	without damping
	1	with damping
base_pres	100000.	Base state surface pressure (Pa), real only. Do not change.
base_temp	290.	Base state sea level temperature (K), real only.
base_lapse	50.	real-data ONLY, lapse rate (K), DO NOT CHANGE.
iso_temp	0.	isothermal temperature in stratosphere, real only, enable the model to be extended to 5 mb
use_baseparm_fr_nml	.false.	for backward compatibility: to use with old wrfinput file
khdif (max_dom)	0	horizontal diffusion constant (m^2/s)
kvdif (max_dom)	0	vertical diffusion constant (m^2/s)
smdiv (max_dom)	0.1	divergence damping (0.1 is typical)
emdiv (max_dom)	0.01	external-mode filter coef for mass coordinate model (0.01 is typical for real-data cases)

epssm (max_dom)	.1	time off-centering for vertical sound waves
non_hydrostatic (max_dom)	.true.	whether running the model in hydrostatic or non-hydro mode
pert_coriolis (max_dom)	.false.	Coriolis only acts on wind perturbation (idealized)
top_lid (max_dom)	.false.	zero vertical motion at top of domain (idealized)
mix_full_fields	.false.	used with diff_opt = 2; value of ".true." is recommended, except for highly idealized numerical tests; damp_opt must not be 1 if ".true." is chosen. .false. means subtract 1-d base-state profile before mixing (idealized)
mix_isotropic(max_dom)	0	0=anistropic vertical/horizontal diffusion coeffs, 1=isotropic, for km_opt = 2, 3
mix_upper_bound(max_dom)	0.1	non-dimensional upper limit for diffusion coeffs, for km_opt = 2, 3
h_mom_adv_order (max_dom)	5	horizontal momentum advection order (5=5th, etc.)
v_mom_adv_order (max_dom)	3	vertical momentum advection order
h_sca_adv_order (max_dom)	5	horizontal scalar advection order
v_sca_adv_order (max_dom)	3	vertical scalar advection order
time_step_sound (max_dom)	4	number of sound steps per time-step (if using a time_step much larger than 6*dx (in km), increase number of sound steps). = 0: the value computed automatically
moist_adv_opt (max_dom)		positive-definite or monotonic advection; 0= none
	1	positive-define advection of moisture
	2	monotonic option
scalar_adv_opt (max_dom)	1	positive-define advection of scalars
	2	monotonic
tke_adv_opt (max_dom)	1	positive-define advection of tke
	2	monotomic
chem_adv_opt (max_dom)	1	positive-define advection of chem vars
	2	monotonic
tracer_adv_opt (max_dom)	1	positive-define advection of tracer (WRF-Chem activated)

	2	monotonic
tke_drag_coefficient (max_dom)	0	surface drag coefficient (Cd, dimensionless) for diff_opt=2 only
tke_heat_flux (max_dom)	0	surface thermal flux (H/rho*cp), K m/s) for diff_opt = 2 only
fft_filter_lat	45.	the latitude above which the polar filter is turned on for global model
gwd_opt	0	gravity wave drag option (1= on), use when grid size > 10 km
do_avgflx_em (max_dom)	0	whether to output time-averaged mass-coupled advective velocities
do_avgflx_cugd	0	whether to output time-averaged convective mass-fluxes from Grell-Devenyi ensemble scheme
sfs_opt (max_dom)	0	nonlinear backscatter and anisotropy (NBA); default off
	1	using diagnostic stress terms (km_opt=2,3 for scalars)
	2	using tke-based stress terms (km_opt=2 needed)
m_opt (max_dom)	0	=1: adds output of Mij stress terms when NBA is not used
tracer_opt (max_dom)	0	=2: activate 8 pre-defined tracers in Registry
&bdy_control		*boundary condition control*
spec_bdy_width	5	total number of rows for specified boundary value nudging
spec_zone	1	number of points in specified zone (spec b.c. option)
relax_zone	4	number of points in relaxation zone (spec b.c. option)
specified (max_dom)	.false.	specified boundary conditions (only can be used for to domain 1)
spec_exp	0.	exponential multiplier for relaxation zone ramp for specified=.t. (0.= linear ramp default; 0.33=~3*dx exp decay factor)
		The above 5 namelists are used for real-data runs only
periodic_x (max_dom)	.false.	periodic boundary conditions in x direction

symmetric_xs (max_dom)	.false.	symmetric boundary conditions at x start (west)
symmetric_xe (max_dom)	.false.	symmetric boundary conditions at x end (east)
open_xs (max_dom)	.false.	open boundary conditions at x start (west)
open_xe (max_dom)	.false.	open boundary conditions at x end (east)
periodic_y (max_dom)	.false.	periodic boundary conditions in y direction
symmetric_ys (max_dom)	.false.	symmetric boundary conditions at y start (south)
symmetric_ye (max_dom)	.false.	symmetric boundary conditions at y end (north)
open_ys (max_dom)	.false.	open boundary conditions at y start (south)
open_ye (max_dom)	.false.	open boundary conditions at y end (north)
nested (max_dom)	.false.,.true.,.true.,	nested boundary conditions (must be set to .true. for nests)
polar	.false.	polar boundary condition (v=0 at polarward-most v-point) for global application
constant_bc	.false.	constant boundary condition used with DFI.

&namelist_quilt

Option for asynchronized I/O for MPI applications

nio_tasks_per_group	0	default value is 0: no quilting; > 0: the number of processors used for IO quilting per IO group
nio_groups	1	default 1. Maybe set to higher value for nesting IO, or history and restart IO

&grib2

background_proc_id	255	Background generating process identifier, typically defined by the originating center to identify the background data that was used in creating the data. This is octet 13 of Section 4 in the grib2 message
forecast_proc_id	255	Analysis or generating forecast process identifier, typically defined by the originating center to identify the forecast process that was used to generate the data. This is octet 14 of Section 4 in the grib2 message

production_status	255	Production status of processed data in the grib2 message. See Code Table 1.3 of the grib2 manual. This is octet 20 of Section 1 in the grib2 record
compression	40	The compression method to encode the output grib2 message. Only 40 for jpeg2000 or 41 for PNG are supported
dfi_radar	0	DFI radar data assimilation switch
&dfi_control	digital filter option control (does not yet support nesting)	
dfi_opt	3	which DFI option to use 0: no digital filter initialization 1: digital filter launch (DFL) 2: diabatic DFI (DDFI) 3: twice DFI (TDFI) (recommended)
dfi_nfilter	7	digital filter type: 0 – uniform; 1- Lanczos; 2 – Hamming; 3 – Blackman; 4 – Kaiser; 5 – Potter; 6 – Dolph window; 7 – Dolph (recommended); 8 – recursive high-order
dfi_write_filtered_input	.true.	whether to write wrfinput file with filtered model state before beginning forecast
dfi_write_dfi_history	.false.	whether to write wrfout files during filtering integration
dfi_cutoff_seconds	3600	cutoff period, in seconds, for the filter. Should not be longer than the filter window
dfi_time_dim	1000	maximum number of time steps for filtering period, this value can be larger than necessary
dfi_bckstop_year	2001	four-digit year of stop time for backward DFI integration. For a model that starts from 2001061112, this specifies 1 hour backward integration
dfi_bckstop_month	06	two-digit month of stop time for backward DFI integration
dfi_bckstop_day	11	two-digit day of stop time for backward DFI integration
dfi_bckstop_hour	11	two-digit hour of stop time for backward DFI integration
dfi_bckstop_minute	00	two-digit minute of stop time for backward DFI integration
dfi_bckstop_second	00	two-digit second of stop time for backward DFI integration

dfi_fwdstop_year	2001	four-digit year of stop time for forward DFI integration. For a model that starts at 2001061112, this specifies 30 minutes of forward integration
dfi_fwdstop_month	06	two-digit month of stop time for forward DFI integration
dfi_fwdstop_day	11	two-digit day of stop time for forward DFI integration
dfi_fwdstop_hour	12	two-digit hour of stop time for forward DFI integration
dfi_fwdstop_minute	30	two-digit minute of stop time for forward DFI integration
dfi_fwdstop_second	00	two-digit second of stop time for forward DFI integration
dfi_radar	0	DFI radar DA switch
&scm		*for single column model option only*
scm_force	1	switch for single column forcing (=0 off)
scm_force_dx	4000.	DX for SCM forcing (in meters)
num_force_layers	8	number of SCM input forcing layers
scm_lu_index	2	SCM landuse category (2 is dryland, cropland and pasture)
scm_isltyp	4	SCM soil category (4 is silt loam)
scm_vegfra	0.5	SCM vegetation fraction
scm_canwat	0.0	SCM canopy water
scm_lat	37.	SCM latitude
scm_lon	-96.	SCM longitude
scm_th_adv	.true.	turn on theta advection in SCM
scm_wind_adv	.true.	turn on wind advection in SCM
scm_qv_adv	.true.	turn on moisture advection in SCM
scm_vert_adv	.true.	turn on vertical advection in SCM
&tc	*controls for tc_em.exe only*	
insert_bogus_storm	.false.	T/F for inserting a bogus tropical storm
remove_storm	.false.	T/F for only removing the original TC
num_storm	1	number of bogus TC
latc_loc	-999.	center latitude of the bogus TC
lonc_loc	-999.	center longitude of the bogus TC
vmax_meters_per_second	-999.	vmax of bogus storm in meters per second
rmax	-999.	maximum radius outward from storm

		center
vmax_ratio	-999.	ratio for representative maximum winds, 0.75 for 45 km grid, and 0.9 for 15 km grid

WRF Output Fields

List of Fields

The following is an edited output list from netCDF command *'ncdump'*. Note that valid output fields will depend on the model options used. If the fields have zero values, then the fields are not computed by the model options selected.

```
ncdump -h wrfout_d<domain>_<date>
```

```
netcdf wrfout_d01_2000-01-24_12:00:00

dimensions:
        Time = UNLIMITED ; // (1 currently)
        DateStrLen = 19 ;
        west_east = 73 ;
        south_north = 60 ;
        bottom_top = 27 ;
        bottom_top_stag = 28 ;
        soil_layers_stag = 4 ;
        west_east_stag = 74 ;
        south_north_stag = 61 ;

variables:
 char Times(Time, DateStrLen) ;
 float LU_INDEX(Time, south_north, west_east) ;
        LU_INDEX:description = "LAND USE CATEGORY" ;
        LU_INDEX:units = "" ;
 float ZNU(Time, bottom_top) ;
        ZNU:description = "eta values on half (mass) levels" ;
        ZNU:units = "" ;
 float ZNW(Time, bottom_top_stag) ;
        ZNW:description = "eta values on full (w) levels" ;
        ZNW:units = "" ;
 float ZS(Time, soil_layers_stag) ;
        ZS:description = "DEPTHS OF CENTERS OF SOIL LAYERS" ;
        ZS:units = "m" ;
 float DZS(Time, soil_layers_stag) ;
        DZS:description = "THICKNESSES OF SOIL LAYERS" ;
        DZS:units = "m" ;
 float U(Time, bottom_top, south_north, west_east_stag) ;
        U:description = "x-wind component" ;
        U:units = "m s-1" ;
 float V(Time, bottom_top, south_north_stag, west_east) ;
        V:description = "y-wind component" ;
        V:units = "m s-1" ;
 float W(Time, bottom_top_stag, south_north, west_east) ;
        W:description = "z-wind component" ;
        W:units = "m s-1" ;
 float PH(Time, bottom_top_stag, south_north, west_east) ;
        PH:description = "perturbation geopotential" ;
        PH:units = "m2 s-2" ;
 float PHB(Time, bottom_top_stag, south_north, west_east) ;
```

```
       PHB:description = "base-state geopotential" ;
       PHB:units = "m2 s-2" ;
float T(Time, bottom_top, south_north, west_east) ;
       T:description = "perturbation potential temperature (theta-t0)" ;
       T:units = "K" ;
float MU(Time, south_north, west_east) ;
       MU:description = "perturbation dry air mass in column" ;
       MU:units = "Pa" ;
float MUB(Time, south_north, west_east) ;
       MUB:description = "base state dry air mass in column" ;
       MUB:units = "Pa" ;
float NEST_POS(Time, south_north, west_east) ;
       NEST_POS:description = "-" ;
       NEST_POS:units = "-" ;
float P(Time, bottom_top, south_north, west_east) ;
       P:description = "perturbation pressure" ;
       P:units = "Pa" ;
float PB(Time, bottom_top, south_north, west_east) ;
       PB:description = "BASE STATE PRESSURE" ;
       PB:units = "Pa" ;
float SR(Time, south_north, west_east) ;
       SR:description = "fraction of frozen precipitation" ;
       SR:units = "-" ;
float POTEVP(Time, south_north, west_east) ;
       POTEVP:description = "accumulated potential evaporation" ;
       POTEVP:units = "W m-2" ;
float SNOPCX(Time, south_north, west_east) ;
       SNOPCX:description = "snow phase change heat flux" ;
       SNOPCX:units = "W m-2" ;
float SOILTB(Time, south_north, west_east) ;
       SOILTB:description = "bottom soil temperature" ;
       SOILTB:units = "K" ;
float FNM(Time, bottom_top) ;
       FNM:description = "upper weight for vertical stretching" ;
       FNM:units = "" ;
float FNP(Time, bottom_top) ;
       FNP:description = "lower weight for vertical stretching" ;
       FNP:units = "" ;
float RDNW(Time, bottom_top) ;
       RDNW:description = "inverse d(eta) values between full (w) levels" ;
       RDNW:units = "" ;
float RDN(Time, bottom_top) ;
       RDN:description = "inverse d(eta) values between half (mass) levels" ;
       RDN:units = "" ;
float DNW(Time, bottom_top) ;
       DNW:description = "d(eta) values between full (w) levels" ;
       DNW:units = "" ;
float DN(Time, bottom_top) ;
       DN:description = "d(eta) values between half (mass) levels" ;
       DN:units = "" ;
float CFN(Time) ;
       CFN:description = "extrapolation constant" ;
       CFN:units = "" ;
float CFN1(Time) ;
       CFN1:description = "extrapolation constant" ;
       CFN1:units = "" ;
float Q2(Time, south_north, west_east) ;
       Q2:description = "QV at 2 M" ;
       Q2:units = "kg kg-1" ;
float T2(Time, south_north, west_east) ;
       T2:description = "TEMP at 2 M" ;
       T2:units = "K" ;
float TH2(Time, south_north, west_east) ;
       TH2:description = "POT TEMP at 2 M" ;
       TH2:units = "K" ;
float PSFC(Time, south_north, west_east) ;
       PSFC:description = "SFC PRESSURE" ;
       PSFC:units = "Pa" ;
float U10(Time, south_north, west_east) ;
       U10:description = "U at 10 M" ;
       U10:units = "m s-1" ;
float V10(Time, south_north, west_east) ;
```

```
       V10:description = "V at 10 M" ;
       V10:units = "m s-1" ;
float RDX(Time) ;
       RDX:description = "INVERSE X GRID LENGTH" ;
       RDX:units = "" ;
float RDY(Time) ;
       RDY:description = "INVERSE Y GRID LENGTH" ;
       RDY:units = "" ;
float RESM(Time) ;
       RESM:description = "TIME WEIGHT CONSTANT FOR SMALL STEPS" ;
       RESM:units = "" ;
float ZETATOP(Time) ;
       ZETATOP:description = "ZETA AT MODEL TOP" ;
       ZETATOP:units = "" ;
float CF1(Time) ;
       CF1:description = "2nd order extrapolation constant" ;
       CF1:units = "" ;
float CF2(Time) ;
       CF2:description = "2nd order extrapolation constant" ;
       CF2:units = "" ;
float CF3(Time) ;
       CF3:description = "2nd order extrapolation constant" ;
       CF3:units = "" ;
int ITIMESTEP(Time) ;
       ITIMESTEP:description = "" ;
       ITIMESTEP:units = "" ;
float XTIME(Time) ;
       XTIME:description = "minutes since simulation start" ;
       XTIME:units = "" ;
float QVAPOR(Time, bottom_top, south_north, west_east) ;
       QVAPOR:description = "Water vapor mixing ratio" ;
       QVAPOR:units = "kg kg-1" ;
float QCLOUD(Time, bottom_top, south_north, west_east) ;
       QCLOUD:description = "Cloud water mixing ratio" ;
       QCLOUD:units = "kg kg-1" ;
float QRAIN(Time, bottom_top, south_north, west_east) ;
       QRAIN:description = "Rain water mixing ratio" ;
       QRAIN:units = "kg kg-1" ;
float LANDMASK(Time, south_north, west_east) ;
       LANDMASK:description = "LAND MASK (1 FOR LAND, 0 FOR WATER)" ;
       LANDMASK:units = "" ;
float TSLB(Time, soil_layers_stag, south_north, west_east) ;
       TSLB:description = "SOIL TEMPERATURE" ;
       TSLB:units = "K" ;
float SMOIS(Time, soil_layers_stag, south_north, west_east) ;
       SMOIS:description = "SOIL MOISTURE" ;
       SMOIS:units = "m3 m-3" ;
float SH2O(Time, soil_layers_stag, south_north, west_east) ;
       SH2O:description = "SOIL LIQUID WATER" ;
       SH2O:units = "m3 m-3" ;
float SEAICE(Time, south_north, west_east) ;
       SEAICE:description = "SEA ICE FLAG" ;
       SEAICE:units = "" ;
float XICEM(Time, south_north, west_east) ;
       XICEM:description = "SEA ICE FLAG (PREVIOUS STEP)" ;
       XICEM:units = "" ;
float SFROFF(Time, south_north, west_east) ;
       SFROFF:description = "SURFACE RUNOFF" ;
       SFROFF:units = "mm" ;
float UDROFF(Time, south_north, west_east) ;
       UDROFF:description = "UNDERGROUND RUNOFF" ;
       UDROFF:units = "mm" ;
int IVGTYP(Time, south_north, west_east) ;
       IVGTYP:description = "DOMINANT VEGETATION CATEGORY" ;
       IVGTYP:units = "" ;
int ISLTYP(Time, south_north, west_east) ;
       ISLTYP:description = "DOMINANT SOIL CATEGORY" ;
       ISLTYP:units = "" ;
float VEGFRA(Time, south_north, west_east) ;
       VEGFRA:description = "VEGETATION FRACTION" ;
       VEGFRA:units = "" ;
float GRDFLX(Time, south_north, west_east) ;
```

```
       GRDFLX:description = "GROUND HEAT FLUX" ;
       GRDFLX:units = "W m-2" ;
float SNOW(Time, south_north, west_east) ;
       SNOW:description = "SNOW WATER EQUIVALENT" ;
       SNOW:units = "kg m-2" ;
float SNOWH(Time, south_north, west_east) ;
       SNOWH:description = "PHYSICAL SNOW DEPTH" ;
       SNOWH:units = "m" ;
float RHOSN(Time, south_north, west_east) ;
       RHOSN:description = " SNOW DENSITY" ;
       RHOSN:units = "kg m-3" ;
float CANWAT(Time, south_north, west_east) ;
       CANWAT:description = "CANOPY WATER" ;
       CANWAT:units = "kg m-2" ;
float SST(Time, south_north, west_east) ;
       SST:description = "SEA SURFACE TEMPERATURE" ;
       SST:units = "K" ;
float QNDROPSOURCE(Time, bottom_top, south_north, west_east) ;
       QNDROPSOURCE:description = "Droplet number source" ;
       QNDROPSOURCE:units = " /kg/s" ;
float MAPFAC_M(Time, south_north, west_east) ;
       MAPFAC_M:description = "Map scale factor on mass grid" ;
       MAPFAC_M:units = "" ;
float MAPFAC_U(Time, south_north, west_east_stag) ;
       MAPFAC_U:description = "Map scale factor on u-grid" ;
       MAPFAC_U:units = "" ;
float MAPFAC_V(Time, south_north_stag, west_east) ;
       MAPFAC_V:description = "Map scale factor on v-grid" ;
       MAPFAC_V:units = "" ;
float MAPFAC_MX(Time, south_north, west_east) ;
       MAPFAC_MX:description = "Map scale factor on mass grid, x direction" ;
       MAPFAC_MX:units = "" ;
float MAPFAC_MY(Time, south_north, west_east) ;
       MAPFAC_MY:description = "Map scale factor on mass grid, y direction" ;
       MAPFAC_MY:units = "" ;
float MAPFAC_UX(Time, south_north, west_east_stag) ;
       MAPFAC_UX:description = "Map scale factor on u-grid, x direction" ;
       MAPFAC_UX:units = "" ;
float MAPFAC_UY(Time, south_north, west_east_stag) ;
       MAPFAC_UY:description = "Map scale factor on u-grid, y direction" ;
       MAPFAC_UY:units = "" ;
float MAPFAC_VX(Time, south_north_stag, west_east) ;
       MAPFAC_VX:description = "Map scale factor on v-grid, x direction" ;
       MAPFAC_VX:units = "" ;
float MF_VX_INV(Time, south_north_stag, west_east) ;
       MF_VX_INV:description = "Inverse map scale factor on v-grid, x direction"
       MF_VX_INV:units = "" ;
float MAPFAC_VY(Time, south_north_stag, west_east) ;
       MAPFAC_VY:description = "Map scale factor on v-grid, y direction" ;
       MAPFAC_VY:units = "" ;
float F(Time, south_north, west_east) ;
       F:description = "Coriolis sine latitude term" ;
       F:units = "s-1" ;
float E(Time, south_north, west_east) ;
       E:description = "Coriolis cosine latitude term" ;
       E:units = "s-1" ;
float SINALPHA(Time, south_north, west_east) ;
       SINALPHA:description = "Local sine of map rotation" ;
       SINALPHA:units = "" ;
float COSALPHA(Time, south_north, west_east) ;
       COSALPHA:description = "Local cosine of map rotation" ;
       COSALPHA:units = "" ;
float HGT(Time, south_north, west_east) ;
       HGT:description = "Terrain Height" ;
       HGT:units = "m" ;
float HGT_SHAD(Time, south_north, west_east) ;
       HGT_SHAD:description = "Height of orographic shadow" ;
       HGT_SHAD:units = "m" ;
float TSK(Time, south_north, west_east) ;
       TSK:description = "SURFACE SKIN TEMPERATURE" ;
       TSK:units = "K" ;
float P_TOP(Time) ;
```

```
       P_TOP:description = "PRESSURE TOP OF THE MODEL" ;
       P_TOP:units = "Pa" ;
float MAX_MSTFX(Time) ;
       MAX_MSTFX:description = "Max map factor in domain" ;
       MAX_MSTFX:units = "" ;
float MAX_MSTFY(Time) ;
       MAX_MSTFY:description = "Max map factor in domain" ;
       MAX_MSTFY:units = "" ;
float RAINC(Time, south_north, west_east) ;
       RAINC:description = "ACCUMULATED TOTAL CUMULUS PRECIPITATION" ;
       RAINC:units = "mm" ;
float RAINNC(Time, south_north, west_east) ;
       RAINNC:description = "ACCUMULATED TOTAL GRID SCALE PRECIPITATION" ;
       RAINNC:units = "mm" ;
float PRATEC(Time, south_north, west_east) ;
       PRATEC:description = "PRECIP RATE FROM CUMULUS SCHEME" ;
       PRATEC:units = "mm s-1" ;
float RAINCV(Time, south_north, west_east) ;
       RAINCV:description = "TIME-STEP CUMULUS PRECIPITATION" ;
       RAINCV:units = "mm" ;
float SNOWNC(Time, south_north, west_east) ;
       SNOWNC:description = "ACCUMULATED TOTAL GRID SCALE SNOW AND ICE" ;
       SNOWNC:units = "mm" ;
float GRAUPELNC(Time, south_north, west_east) ;
       GRAUPELNC:description = "ACCUMULATED TOTAL GRID SCALE GRAUPEL" ;
       GRAUPELNC:units = "mm" ;
float EDT_OUT(Time, south_north, west_east) ;
       EDT_OUT:description = "EDT FROM GD SCHEME" ;
       EDT_OUT:units = "" ;
float SWDOWN(Time, south_north, west_east) ;
       SWDOWN:description = "DOWNWARD SHORT WAVE FLUX AT GROUND SURFACE" ;
       SWDOWN:units = "W m-2" ;
float GLW(Time, south_north, west_east) ;
       GLW:description = "DOWNWARD LONG WAVE FLUX AT GROUND SURFACE" ;
       GLW:units = "W m-2" ;
float OLR(Time, south_north, west_east) ;
       OLR:description = "TOA OUTGOING LONG WAVE" ;
       OLR:units = "W m-2" ;
float XLAT(Time, south_north, west_east) ;
       XLAT:description = "LATITUDE, SOUTH IS NEGATIVE" ;
       XLAT:units = "degree_north" ;
float XLONG(Time, south_north, west_east) ;
       XLONG:description = "LONGITUDE, WEST IS NEGATIVE" ;
       XLONG:units = "degree_east" ;
float XLAT_U(Time, south_north, west_east_stag) ;
       XLAT_U:description = "LATITUDE, SOUTH IS NEGATIVE" ;
       XLAT_U:units = "degree_north" ;
float XLONG_U(Time, south_north, west_east_stag) ;
       XLONG_U:description = "LONGITUDE, WEST IS NEGATIVE" ;
       XLONG_U:units = "degree_east" ;
float XLAT_V(Time, south_north_stag, west_east) ;
       XLAT_V:description = "LATITUDE, SOUTH IS NEGATIVE" ;
       XLAT_V:units = "degree_north" ;
float XLONG_V(Time, south_north_stag, west_east) ;
       XLONG_V:description = "LONGITUDE, WEST IS NEGATIVE" ;
       XLONG_V:units = "degree_east" ;
float ALBEDO(Time, south_north, west_east) ;
       ALBEDO:description = "ALBEDO" ;
       ALBEDO:units = "-" ;
float ALBBCK(Time, south_north, west_east) ;
       ALBBCK:description = "BACKGROUND ALBEDO" ;
       ALBBCK:units = "" ;
float EMISS(Time, south_north, west_east) ;
       EMISS:description = "SURFACE EMISSIVITY" ;
       EMISS:units = "" ;
float TMN(Time, south_north, west_east) ;
       TMN:description = "SOIL TEMPERATURE AT LOWER BOUNDARY" ;
       TMN:units = "K" ;
float XLAND(Time, south_north, west_east) ;
       XLAND:description = "LAND MASK (1 FOR LAND, 2 FOR WATER)" ;
       XLAND:units = "" ;
float UST(Time, south_north, west_east) ;
```

```
       UST:description = "U* IN SIMILARITY THEORY" ;
       UST:units = "m s-1" ;
float PBLH(Time, south_north, west_east) ;
       PBLH:description = "PBL HEIGHT" ;
       PBLH:units = "m" ;
float HFX(Time, south_north, west_east) ;
       HFX:description = "UPWARD HEAT FLUX AT THE SURFACE" ;
       HFX:units = "W m-2" ;
float QFX(Time, south_north, west_east) ;
       QFX:description = "UPWARD MOISTURE FLUX AT THE SURFACE" ;
       QFX:units = "kg m-2 s-1" ;
float LH(Time, south_north, west_east) ;
       LH:description = "LATENT HEAT FLUX AT THE SURFACE" ;
       LH:units = "W m-2" ;
float SNOWC(Time, south_north, west_east) ;
       SNOWC:description = "FLAG INDICATING SNOW COVERAGE (1 FOR SNOW COVER)" ;
       SNOWC:units = "" ;
```

Special WRF Output Variables

WRF model outputs the state variables defined in the Registry file, and these state variables are used in the model's prognostic equations. Some of these variables are perturbation fields. Therefore some definition for reconstructing meteorological variables is necessary. In particular, the definitions for the following variables are:

total geopotential	`PH + PHB`
total geopotential height in m	`( PH + PHB ) / 9.81`
total potential temperature in_ K	`T + 300`
total pressure in mb	`( P + PB ) * 0.01`
wind compoments, grid relative	`U, V`
surface pressure in Pa	`psfc`
surface winds, grid relative	`U10, V10 (valid at mass points)`
surface temperature and mixing ratio	`T2, Q2`

The definition for map projection options:

`map_proj` =	1: Lambert Conformal
	2: Polar Stereographic
	3: Mercator
	6: latitude and longitude (including global)

List of Global Attributes

```
// global attributes:

       :TITLE = " OUTPUT FROM WRF V3.0.1.1 MODEL" ;
```

```
:START_DATE = "2000-01-24_12:00:00" ;
:SIMULATION_START_DATE = "2000-01-24_12:00:00" ;
:WEST-EAST_GRID_DIMENSION = 74 ;
:SOUTH-NORTH_GRID_DIMENSION = 61 ;
:BOTTOM-TOP_GRID_DIMENSION = 28 ;
:DX = 30000.f ;
:DY = 30000.f ;
:GRIDTYPE = "C" ;
:DIFF_OPT = 1 ;
:KM_OPT = 4 ;
:DAMP_OPT = 0 ;
:KHDIF = 0.f ;
:KVDIF = 0.f ;
:MP_PHYSICS = 3 ;
:RA_LW_PHYSICS = 1 ;
:RA_SW_PHYSICS = 1 ;
:SF_SFCLAY_PHYSICS = 1 ;
:SF_SURFACE_PHYSICS = 2 ;
:BL_PBL_PHYSICS = 1 ;
:CU_PHYSICS = 1 ;
:SURFACE_INPUT_SOURCE = 1 ;
:SST_UPDATE = 0 ;
:GRID_FDDA = 1 ;
:GFDDA_INTERVAL_M = 360 ;
:GFDDA_END_H = 24 ;
:UCMCALL = 0 ;
:FEEDBACK = 1 ;
:SMOOTH_OPTION = 0 ;
:SWRAD_SCAT = 1.f ;
:W_DAMPING = 0 ;
:MOIST_ADV_OPT = 1 ;
:SCALAR_ADV_OPT = 1 ;
:TKE_ADV_OPT = 0 ;
:DIFF_6TH_OPT = 0 ;
:DIFF_6TH_FACTOR = 0.12f ;
:OBS_NUDGE_OPT = 0 ;
:BUCKET_MM = -1.f ;
:BUCKET_J = -1.f ;
:PREC_ACC_DT = 60.f ;
:OMLCALL = 0 ;
:FGDT = 0.f ;
:GUV = 0.0003f ;
:GT = 0.0003f ;
:GQ = 0.0003f ;
:IF_RAMPING = 1 ;
:DTRAMP_MIN = 60.f ;
:OBS_NUDGE_OPT = 0 ;
:WEST-EAST_PATCH_START_UNSTAG = 1 ;
:WEST-EAST_PATCH_END_UNSTAG = 73 ;
:WEST-EAST_PATCH_START_STAG = 1 ;
:WEST-EAST_PATCH_END_STAG = 74 ;
:SOUTH-NORTH_PATCH_START_UNSTAG = 1 ;
:SOUTH-NORTH_PATCH_END_UNSTAG = 60 ;
:SOUTH-NORTH_PATCH_START_STAG = 1 ;
:SOUTH-NORTH_PATCH_END_STAG = 61 ;
:BOTTOM-TOP_PATCH_START_UNSTAG = 1 ;
:BOTTOM-TOP_PATCH_END_UNSTAG = 27 ;
:BOTTOM-TOP_PATCH_START_STAG = 1 ;
:BOTTOM-TOP_PATCH_END_STAG = 28 ;
:GRID_ID = 1 ;
:PARENT_ID = 0 ;
:I_PARENT_START = 1 ;
:J_PARENT_START = 1 ;
:PARENT_GRID_RATIO = 1 ;
:DT = 180.f ;
:CEN_LAT = 34.83002f ;
:CEN_LON = -81.03f ;
:TRUELAT1 = 30.f ;
:TRUELAT2 = 60.f ;
:MOAD_CEN_LAT = 34.83002f ;
:STAND_LON = -98.f ;
:GMT = 12.f ;
```

```
:JULYR = 2000 ;
:JULDAY = 24 ;
:MAP_PROJ = 1 ;
:MMINLU = "USGS" ;
:NUM_LAND_CAT = 24 ;
:ISWATER = 16 ;
:ISICE = 24 ;
:ISURBAN = 1 ;
:ISOILWATER = 14 ;
```

Chapter 6: WRF Data Assimilation

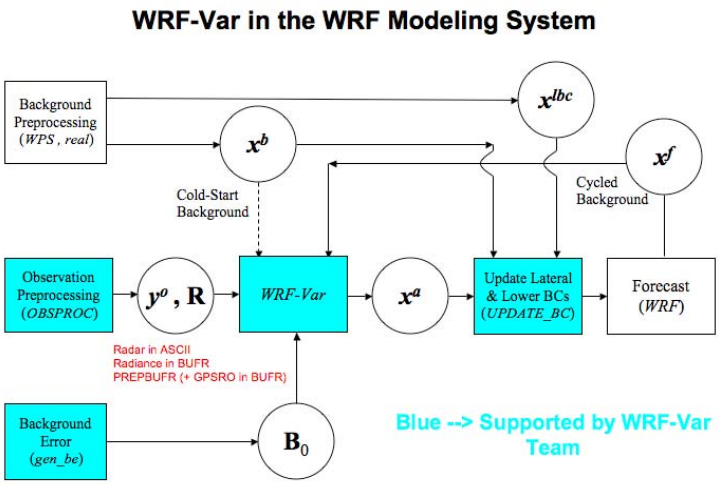
Table of Contents

Introduction

Data assimilation is the technique by which **observations** are combined with a NWP product (the **first guess** or background forecast) and their respective error statistics to provide an improved estimate (the **analysis**) of the atmospheric (or oceanic, Jovian, whatever) state. Variational (Var) data assimilation achieves this through the iterative minimization of a prescribed cost (or penalty) function. Differences between the analysis and observations/first guess are penalized (damped) according to their perceived error. The difference between three-dimensional (3D-Var) and four-dimensional (4D-Var) data assimilation is the use of a numerical forecast model in the latter.

The MMM Division of NCAR supports a unified (global/regional, multi-model, 3/4D-Var) model-space data assimilation system (WRFDA) for use by NCAR staff and collaborators, and is also freely available to the general community, together with further documentation, test results, plans etc., from the WRFDA web-page http://www.mmm.ucar.edu/wrf/users/wrfda/Docs/user_guide_V3.2/users_guide_chap6.htm.

Various components of the WRFDA system are shown in blue in the sketch below, together with their relationship with rest of the WRF system.



x^b: first guess either from previous WRF forecast or from WPS/REAL output.

x^{lbc}: lateral boundary from WPS/REAL output.

x^a: analysis from WRFDA data assimilation system.

x^f: WRF forecast output.

y^o: observations processed by OBSPROC. (note: PREPBUFR input, Radar and Radiance data don't go through OBSPROC)

B_0: background error statistics from generic BE data (CV3) or gen_be.

R: observational and representative error statistics.

In this chapter, you will learn how to run the various components of WRFDA system. For the training purpose, you are supplied with a test case including the following input data: a) observation file (in the format prior to OBSPROC), b) WRF NetCDF background file (WPS/REAL output used as a first guess of the analysis), and c) Background error statistics (estimate of errors in the background file). You can download the test dataset from http://www.mmm.ucar.edu/wrf/users/wrfda/download/testdata.html. In your own work, you have to create all these input files yourselves. See the section Running Observation Preprocessor for creating your observation files. See section Running gen_be for generating your background error statistics file if you want to use cv_options=5.

Before using your own data, we suggest that you start by running through the WRFDA related programs at least once using the supplied test case. This serves two purposes: First, you can learn how to run the programs with data we have tested ourselves, and second you can test whether your computer is adequate to run the entire modeling system.

After you have done the tutorial, you can try running other, more computationally intensive, case studies and experimenting with some of the many namelist variables.

WARNING: It is impossible to test every code upgrade with every permutation of computer, compiler, number of processors, case, namelist option, etc. The "namelist" options that are supported are indicated in the "`WRFDA/var/README.namelist`" and these are the default options.

Running with your own domain. Hopefully, our test cases will have prepared you for the variety of ways in which you may wish to run WRFDA. Please inform us about your experiences.

As a professional courtesy, we request that you include the following reference in any publications that makes use of any component of the community WRFDA system:

Barker, D.M., W. Huang, Y.R. Guo, and Q.N. Xiao., 2004: A Three-Dimensional (3DVAR) Data Assimilation System For Use With MM5: Implementation and Initial Results. *Mon. Wea. Rev*., **132**, 897-914.

Huang, X.Y., Q. Xiao, D.M. Barker, X. Zhang, J. Michalakes, W. Huang, T. Henderson, J. Bray, Y. Chen, Z. Ma, J. Dudhia, Y. Guo, X. Zhang, D.J. Won, H.C. Lin, and Y.H. Kuo, 2009: Four-Dimensional Variational Data Assimilation for WRF: Formulation and Preliminary Results. Mon. Wea. Rev., 137, 299–314.

Running WRFDA requires a Fortran 90 compiler. We have currently tested the WRFDA on the following platforms: IBM (XLF), SGI Altix (INTEL), PC/Linux (PGI, INTEL, GFORTRAN), and Apple (G95/PGI). Please let us know if this does not meet your requirements, and we will attempt to add other machines to our list of supported architectures as resources allow. Although we are interested to hear of your experiences on modifying compile options, we do not yet recommend making changes to the configure file used to compile WRFDA.

Installing WRFDA

a. Obtaining WRFDA Source Code

Users can download the WRFDA source code from http://www.mmm.ucar.edu/wrf/users/wrfda/download/get_source.html.

After the tar file is unzipped (`gunzip WRFDAV3.2.tar.gz`) and untarred (`untar WRFDAV3.2.tar`), the directory `WRFDA` should be created; this directory contains the

WRFDA source, external libraries, and fixed files. The following is a list of the system components and the content for each directory:

Directory Name	Content
var/da	WRFDA source code
var/run	Fixed input files required by WRFDA, such as background error covariances, and radiance related files CRTM coefficients, radiance_info and VARBC.in.
var/external	Library needed by WRFDA, include crtm, bufr, lapack, blas
var/obsproc	Obsproc source code , namelist, and obser-vation error file.
var/gen_be	Source code of generate background error
var/build	Build all .exe files.

b. Compile WRFDA and Libraries

Start with V3.1.1, to compile the WRFDA code, it is necessary to have installed the NetCDF library. The NetCDF library is the only mandatory library to install WRFDA, if only conventional observational data from LITTLE_R format file is to be used.

Only if you intend to use observational data with PREPBUFR format, an environment variables is needed to be set like (using the C-shell),

```
> setenv BUFR  1
```

In addition to BUFR library, if you intend to assimilate satellite radiance data with CRTM (V2.0.2),

```
> setenv CRTM  1
```

The CRTM will be compiled with WRFDA together. You don't need to install the CRTM separately any more since CRTM V2.0.2. However, if you intend to use RTTOV (8.7) to assimilate radiance data, which still have to be installed separately. RTTOV (8.7) can be downloaded from http://www.metoffice.gov.uk/science/creating/working_together/nwpsaf_public.html. The additional necessary environment variables needed are set (again using the C-shell), by commands looking something like

```
> setenv RTTOV /usr/local/rttov87
(Note: make a linkage of $RTTOV/librttov.a to $RTTOV/src/librttov8.7.a)
```

Note: **Make sure the required libraries were all compiled using the same compiler that will be used to build WRFDA**, since the libraries produced by one compiler may not be compatible with code compiled with another.

Assuming all required libraries are available and the WRFDA source code is ready, start to install the WRFDA as following step:

To configure WRFDA, enter the `WRFDA` directory and type

```
> ./configure wrfda
```

A list of configuration options for your computer should appear. Each option combines a compiler type and a parallelism option; since the configuration script doesn't check which compilers are *actually* available, be sure to only select among the options for compilers that are available on your system. The parallelism option allows for a single-processor (serial) compilation, shared-memory parallel (smpar) compilation, distributed-memory parallel (dmpar) compilation and distributed-memory with shared-memory parallel (sm+dm) compilation. For example, on a Macintosh computer, the above steps look like:

```
> ./configure wrfda

checking for perl5... no
checking for perl... found /usr/bin/perl (perl)
Will use NETCDF in dir: /users/noname/work/external/g95/netcdf-3.6.1
PHDF5 not set in environment. Will configure WRF for use without.
$JASPERLIB or $JASPERINC not found in environment, configuring to build without
grib2 I/O...
------------------------------------------------------------------------
Please select from among the following supported platforms.

   1.  Darwin (MACOS) PGI compiler with pgcc  (serial)
   2.  Darwin (MACOS) PGI compiler with pgcc  (smpar)
   3.  Darwin (MACOS) PGI compiler with pgcc  (dmpar)
   4.  Darwin (MACOS) PGI compiler with pgcc  (dm+sm)
   5.  Darwin (MACOS) intel compiler with icc  (serial)
   6.  Darwin (MACOS) intel compiler with icc  (smpar)
   7.  Darwin (MACOS) intel compiler with icc  (dmpar)
   8.  Darwin (MACOS) intel compiler with icc  (dm+sm)
   9.  Darwin (MACOS) intel compiler with cc  (serial)
  10.  Darwin (MACOS) intel compiler with cc  (smpar)
  11.  Darwin (MACOS) intel compiler with cc  (dmpar)
  12.  Darwin (MACOS) intel compiler with cc  (dm+sm)
  13.  Darwin (MACOS) g95 with gcc  (serial)
  14.  Darwin (MACOS) g95 with gcc  (dmpar)
  15.  Darwin (MACOS) xlf   (serial)
  16.  Darwin (MACOS) xlf   (dmpar)

Enter selection [1-10] : 13
------------------------------------------------------------------------
Compile for nesting? (0=no nesting, 1=basic, 2=preset moves, 3=vortex following)
[default 0]:
Configuration successful. To build the model type compile . compile.
……
```

After running the configuration script and choosing a compilation option, a `configure.wrf` file will be created. Because of the variety of ways that a computer can be configured, if the WRFDA build ultimately fails, there is a chance that minor modifications to the `configure.wrf` file may be needed.

Note: WRF compiles with –r4 option while WRFDA compiles with –r8. For this reason, WRF and WRFDA cannot reside and be compiled under the same directory.

Hint: It is helpful to start with something simple, such as the serial build. If it is successful, move on to build dmpar code. Remember to type '`clean -a`' between each build.

To compile the code, type

```
> ./compile all_wrfvar >&! compile.out
```

Successful compilation of 'all_wrfvar" will produce 32 executables in the `var/build` directory which are linked in `var/da` directory, as well as `obsproc.exe` in `var/obsproc/src` directory. You can list these executables by issuing the command (from `WRFDA` directory)

```
> ls -l var/build/*exe var/obsproc/src/obsproc.exe
-rwxr-xr-x  1 noname  users    641048 Mar 23 09:28 var/build/da_advance_time.exe
-rwxr-xr-x  1 noname  users    954016 Mar 23 09:29 var/build/da_bias_airmass.exe
-rwxr-xr-x  1 noname  users    721140 Mar 23 09:29 var/build/da_bias_scan.exe
-rwxr-xr-x  1 noname  users    686652 Mar 23 09:29 var/build/da_bias_sele.exe
-rwxr-xr-x  1 noname  users    700772 Mar 23 09:29 var/build/da_bias_verif.exe
-rwxr-xr-x  1 noname  users    895300 Mar 23 09:29 var/build/da_rad_diags.exe
-rwxr-xr-x  1 noname  users    742660 Mar 23 09:29 var/build/da_tune_obs_desroziers.exe
-rwxr-xr-x  1 noname  users    942948 Mar 23 09:29
var/build/da_tune_obs_hollingsworth1.exe
-rwxr-xr-x  1 noname  users    913904 Mar 23 09:29
var/build/da_tune_obs_hollingsworth2.exe
-rwxr-xr-x  1 noname  users    943000 Mar 23 09:28 var/build/da_update_bc.exe
-rwxr-xr-x  1 noname  users   1125892 Mar 23 09:29 var/build/da_verif_anal.exe
-rwxr-xr-x  1 noname  users    705200 Mar 23 09:29 var/build/da_verif_obs.exe
-rwxr-xr-x  1 noname  users  46602708 Mar 23 09:28 var/build/da_wrfvar.exe
-rwxr-xr-x  1 noname  users   1938628 Mar 23 09:29 var/build/gen_be_cov2d.exe
-rwxr-xr-x  1 noname  users   1938628 Mar 23 09:29 var/build/gen_be_cov3d.exe
-rwxr-xr-x  1 noname  users   1930436 Mar 23 09:29 var/build/gen_be_diags.exe
-rwxr-xr-x  1 noname  users   1942724 Mar 23 09:29 var/build/gen_be_diags_read.exe
-rwxr-xr-x  1 noname  users   1941268 Mar 23 09:29 var/build/gen_be_ensmean.exe
-rwxr-xr-x  1 noname  users   1955192 Mar 23 09:29 var/build/gen_be_ensrf.exe
-rwxr-xr-x  1 noname  users   1979588 Mar 23 09:28 var/build/gen_be_ep1.exe
-rwxr-xr-x  1 noname  users   1961948 Mar 23 09:28 var/build/gen_be_ep2.exe
-rwxr-xr-x  1 noname  users   1945360 Mar 23 09:29 var/build/gen_be_etkf.exe
-rwxr-xr-x  1 noname  users   1990936 Mar 23 09:28 var/build/gen_be_stage0_wrf.exe
-rwxr-xr-x  1 noname  users   1955012 Mar 23 09:28 var/build/gen_be_stage1.exe
-rwxr-xr-x  1 noname  users   1967296 Mar 23 09:28 var/build/gen_be_stage1_1dvar.exe
-rwxr-xr-x  1 noname  users   1950916 Mar 23 09:28 var/build/gen_be_stage2.exe
-rwxr-xr-x  1 noname  users   2160796 Mar 23 09:29 var/build/gen_be_stage2_1dvar.exe
-rwxr-xr-x  1 noname  users   1942724 Mar 23 09:29 var/build/gen_be_stage2a.exe
-rwxr-xr-x  1 noname  users   1950916 Mar 23 09:29 var/build/gen_be_stage3.exe
-rwxr-xr-x  1 noname  users   1938628 Mar 23 09:29 var/build/gen_be_stage4_global.exe
-rwxr-xr-x  1 noname  users   1938732 Mar 23 09:29 var/build/gen_be_stage4_regional.exe
-rwxr-xr-x  1 noname  users   1094740 Mar 23 09:29 var/build/gen_be_vertloc.exe
-rwxr-xr-x  1 noname  users   1752352 Mar 23 09:29 var/obsproc/src/obsproc.exe
```

`da_wrfvar.exe` is the main executable for running WRFDA. Make sure it is created after the compilation. Sometimes (unfortunately) it is possible that other utilities get successfully compiled, while the main `da_wrfvar.exe` fails; please check the compilation log file carefully to figure out the problem.

The basic gen_be utility for regional model consists of `gen_be_stage0_wrf.exe`, `gen_be_stage1.exe`, `gen_be_stage2.exe`, `gen_be_stage2a.exe`, `gen_be_stage3.exe`, `gen_be_stage4_regional.exe`, and `gen_be_diags.exe`.

`da_updated_bc.exe` is used for updating WRF boundary condition after a new WRFDA analysis is generated.

`da_advance_time.exe` is a very handy and useful tool for date/time manipulation. Type "`da_advance_time.exe`" to see its usage instruction.

In addition to the executables for running WRFDA and gen_be, `obsproc.exe` (the executable for preparing conventional data for WRFDA) compilation is also included in "`./compile all_wrfvar`".

Go to /external/bufr and /external/crtm to check if the libbufr.a and libcrtm.a were generated if you use BUFR and CRTM library.

c. Clean Compilation

To remove all object files and executables, type:

clean

To remove all build files, including configure.wrfda, type:

clean -a

The clean command is recommended if compilation fails or configuration file is changed.

Installing WRFNL and WRFPLUS (For 4D-Var only)

If you intend to run WRF 4D-Var, it is necessary to have installed the WRFNL (WRF nonlinear model) and WRFPLUS (WRF adjoint and tangent linear model). WRFNL is a modified version of WRF V3.2 and can only be used for 4D-Var purposes. WRFPLUS contains the adjoint and tangent linear models based on a simplified WRF model, which only includes some simple physical processes such as vertical diffusion and large-scale condensation.

To install WRFNL:

- Get the WRF zipped tar file from:

  http://www.mmm.ucar.edu/wrf/users/download/get_source.html

- Unzip and untar the file, name the directory WRFNL

  ```
  > cd WRFNL

  > gzip -cd WRFV3.TAR.gz | tar -xf - ; mv WRFV3 WRFNL
  ```

- Get the WRFNL patch zipped tar file from:

  http://www.mmm.ucar.edu/wrf/users/wrfda/download/wrfnl.html

- unzip and untar the WRFNL patch file

```
> gzip -cd WRFNL3.2_PATCH.tar.gz | tar -xf -

> ./configure
```

serial means single processor

dmpar means Distributed Memory Parallel (MPI)

smpar is not supported for 4D-Var

Please select 0 for the second option for no nesting

- Compile the WRFNL

- `> ./compile em_real`
- `> ls -ls main/*.exe`

If you built the real-data case, you should see **`wrf.exe`**

To install WRFPLUS:

- Get the WRFPLUS zipped tar file from:

  http://www.mmm.ucar.edu/wrf/users/wrfda/download/wrfplus.html

- Unzip and untar the file to WRFPLUS

- `> gzip -cd WRFPLUS3.2.tar.gz | tar -xf -`
- `> cd WRFPLUS`
- `> ./configure wrfplus`

serial means single processor

dmpar means Distributed Memory Parallel (MPI)

Note: wrfplus was tested on following platforms:

IBM AIX: xlfrte 11.1.0.5

Linux : pgf90 6.2-5 64-bit target on x86-64 Linux (environmental variable PGHPF_ZMEM=yes is needed)

Mac OS (Intel) : g95 0.91!

- Compile WRFPLUS

- `> ./compile wrf`
- `> ls -ls main/*.exe`

You should see **`wrfplus.exe`**

Running Observation Preprocessor (OBSPROC)

The OBSPROC program reads observations in LITTLE_R format (a legendary ASCII format, in use since MM5 era). Please refer to the documentation at http://www.mmm.ucar.edu/mm5/mm5v3/data/how_to_get_rawdata.html for LITTLE_R format description. For your applications, you will have to prepare your own observation files. Please see http://www.mmm.ucar.edu/mm5/mm5v3/data/free_data.html for the sources of some freely available observations and the program for converting the observations to LITTLE_R format. Because the raw observation data files could be in any of formats, such as ASCII, BUFR, PREPBUFR, MADIS, HDF, etc. Further more, for each of formats, there may be the different versions. To make WRFDA system as general as possible, the LITTLE_R format ASCII file was adopted as an intermediate observation data format for WRFDA system. Some extensions were made in the LITTLE_R format for WRFDA applications. More complete description of LITTLE_R format and conventional observation data sources for WRFDA could be found from the web page: 2010 Winter Tutorial by clicking "Observation Pre-processing". The conversion of the user-specific-source data to the LITTLE_R format observation data file is the users' task.

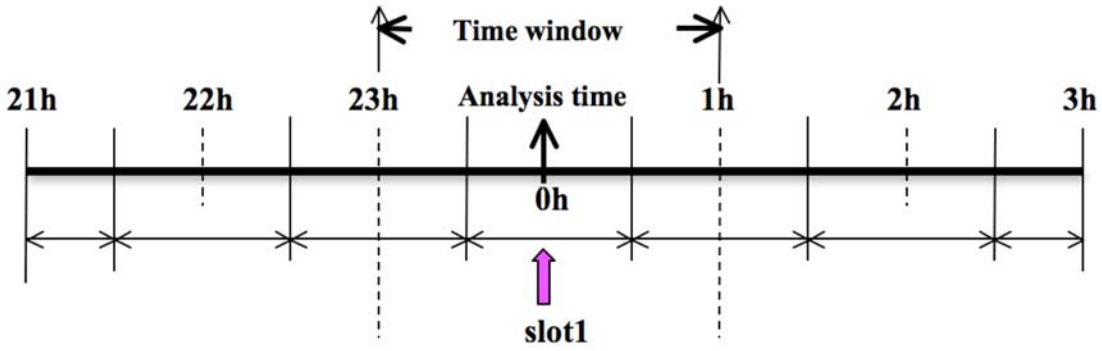
The purposes of OBSPROC are:

- Remove observations outside the time range and domain (horizontal and top).
- Re-order and merge duplicate (in time and location) data reports.
- Retrieve pressure or height based on observed information using the hydrostatic assumption.
- Check vertical consistency and super adiabatic for multi-level observations.
- Assign observational errors based on a pre-specified error file.
- Write out the observation file to be used by WRFDA in ASCII or BUFR format.

The OBSPROC program—`obsproc.exe` should be found under the directory `WRFDA/var/obsproc/src` if "`compile all_wrfvar`" was completed successfully.

a. Prepare observational data for 3D-Var

To prepare the observation file, for example, at the analysis time 0h for 3D-Var, all the observations between ±1h (or ±1.5h) will be processed, as illustrated in following figure, which means that the observations between 23h and 1h are treated as the observations at 0h.



Before running `obsproc.exe`, create the required namelist file `namelist.obsproc` (see `WRFDA/var/obsproc/README.namelist`, or the section Description of Namelist Variables for details).

For your reference, an example file named "`namelist_obsproc.3dvar.wrfvar-tut`" has already been created in the `var/obsproc` directory. Thus, proceed as follows.

```
> cp namelist.obsproc.3dvar.wrfvar-tut namelist.obsproc
```

Next, edit the namelist file `namelist.obsproc` by changing the following variables to accommodate your experiments.

```
&record1
obs_gts_filename='obs.2008020512'

&record2
time_window_min = '2008-02-05_11:00:00',: The earliest time edge as ccyy-mm-dd_hh:mn:ss
time_analysis   = '2008-02-05_12:00:00', : The analysis time as ccyy-mm-dd_hh:mn:ss
time_window_max = '2008-02-05_13:00:00',: The latest time edge as ccyy-mm-dd_hh:mn:ss

&record6,7,8
```

Edit all the domain setting according with your own experiment. You may pay special attention on NESTIX and NESTJX, which is described in the section Description of Namelist Variables for details).

```
&record9
use_for = '3DVAR',  ; used for 3D-Var, default
```

To run OBSPROC, type

```
> obsproc.exe >&! obsproc.out
```

Once `obsproc.exe` has completed successfully, you will see an observation data file, `obs_gts_2008-02-05_12:00:00.3DVAR`, in the `obsproc` directory. This is the input observation file to WRFDA.

obs_gts_2008-02-05_12:00:00.3DVAR is an ASCII file that contains a header section (listed below) followed by observations. The meanings and format of observations in the file are described in the last six lines of the header section.

```
TOTAL =   9066, MISS. =-888888.,
SYNOP =    757, METAR =   2416, SHIP  =    145, BUOY  =    250, BOGUS =      0, TEMP  =
86,
AMDAR =     19, AIREP =    205, TAMDAR=      0, PILOT =     85, SATEM =    106, SATOB =
2556,
GPSPW =    187, GPSZD =      0, GPSRF =      3, GPSEP =      0, SSMT1 =      0, SSMT2 =
0,
TOVS  =      0, QSCAT =   2190, PROFL =     61, AIRSR =      0, OTHER =      0,
PHIC  =  40.00, XLONC = -95.00, TRUE1 =  30.00, TRUE2 =  60.00, XIM11 =   1.00, XJM11 =
1.00,
base_temp= 290.00, base_lapse=  50.00, PTOP  =  1000., base_pres=100000.,
base_tropo_pres= 20000., base_strat_temp=   215.,
IXC   =     60, JXC   =     90, IPROJ =      1, IDD   =      1, MAXNES=      1,
NESTIX=     60,
NESTJX=     90,
NUMC  =      1,
DIS   =  60.00,
NESTI =      1,
NESTJ =      1,
INFO  = PLATFORM, DATE, NAME, LEVELS, LATITUDE, LONGITUDE, ELEVATION, ID.
SRFC  = SLP, PW (DATA,QC,ERROR).
EACH  = PRES, SPEED, DIR, HEIGHT, TEMP, DEW PT, HUMID (DATA,QC,ERROR)*LEVELS.
INFO_FMT = (A12,1X,A19,1X,A40,1X,I6,3(F12.3,11X),6X,A40)
SRFC_FMT = (F12.3,I4,F7.2,F12.3,I4,F7.3)
EACH_FMT = (3(F12.3,I4,F7.2),11X,3(F12.3,I4,F7.2),11X,3(F12.3,I4,F7.2))
#-------------------------------------------------------------------------------#
…… observations ……
```

Before running WRFDA, you may like to learn more about various types of data that will be passed to WRFDA for this case, for example, their geographical distribution, etc. This file is in ASCII format and so you can easily view it. To have a graphical view about the content of this file, there is a "MAP_plot" utility to look at the data distribution for each type of observations. To use this utility, proceed as follows.

```
> cd MAP_plot
> make
```

We have prepared some configure.user.ibm/linux/mac/… files for some platforms, when "make" is typed, the Makefile will use one of them to determine the compiler and compiler option. Please modify the Makefile and configure.user.xxx to accommodate the complier on your platform. Successful compilation will produce Map.exe.
Note: The successful compilation of Map.exe requires pre-installed NCARG Graphics libraries under $(NCARG_ROOT)/lib.

Modify the script Map.csh to set the time window and full path of input observation file (obs_gts_2008-02-05_12:00:00.3DVAR). You will need to set the following strings in this script as follows:

```
Map_plot = /users/noname/WRFDA/var/obsproc/MAP_plot
TIME_WINDOW_MIN = '2008020511'
TIME_ANALYSIS   = '2008020512'
TIME_WINDOW_MAX = '2008020513'
OBSDATA  = ../obs_gts_2008-02-05_12:00:00.3DVAR
```

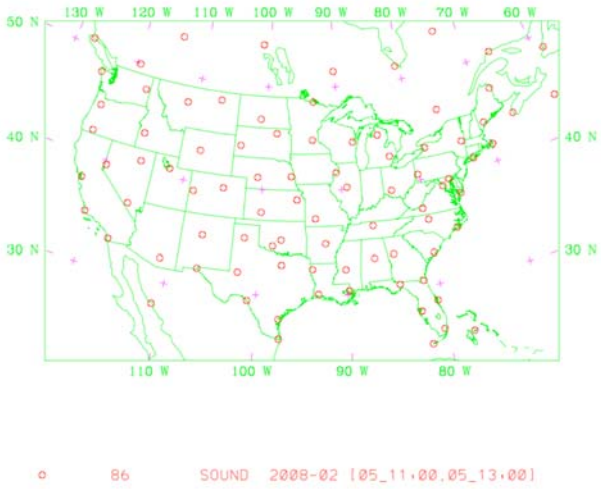
Next, type

```
> Map.csh
```

When the job has completed, you will have a gmeta file `gmeta.{analysis_time}` corresponding to `analysis_time=2008020512`. This contains plots of data distribution for each type of observations contained in the OBS data file: `obs_gts_2008-02-05_12:00:00.3DVAR`. To view this, type

```
> idt gmeta.2008020512
```

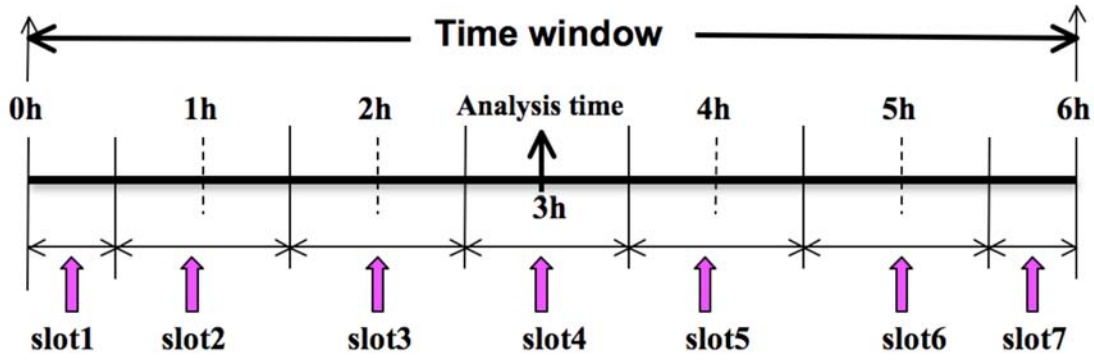
It will display (panel by panel) geographical distribution of various types of data. Following is the geographic distribution of "sonde" observations for this case.



There is an alternative way to plot the observation by using ncl script: `WRFDA/var/graphics/ncl/plot_ob_ascii_loc.ncl`. However, with this way, you need to provide the first guess file to the ncl script, and have ncl installed in your system.

b. Prepare observational data for 4D-Var

To prepare the observation file, for example, at the analysis time 0h for 4D-Var, all observations from 0h to 6h will be processed and grouped in 7 sub-windows from slot1 to slot7, as illustrated in following figure. NOTE: The "Analysis time" in the figure below is not the actual analysis time (0h), it just indicates the time_analysis setting in the namelist file, and is set to three hours later than the actual analysis time. The actual analysis time is still 0h.



An example file named "`namelist_obsproc.4dvar.wrfvar-tut`" has already been created in the `var/obsproc` directory. Thus, proceed as follows:

```
> cp namelist.obsproc.4dvar.wrfvar-tut namelist.obsproc
```

In the namelist file, you need to change the following variables to accommodate your experiments. In this test case, the actual analysis time is `2008-02-05_12:00:00`, but in namelist, the `time_analysis` should be set to 3 hours later. The different value of time_analysis will make the different number of time slots before and after time_analysis. For example, if you set time_analysis = 2008-02-05_16:00:00, and set the num_slots_past = 4 and time_slots_ahead=2. The final results will be same as before.

```
&record1
obs_gts_filename='obs.2008020512'
&record2

time_window_min = '2008-02-05_12:00:00',: The earliest time edge as ccyy-mm-dd_hh:mn:ss
time_analysis   = '2008-02-05_15:00:00', : The analysis time as ccyy-mm-dd_hh:mn:ss
time_window_max = '2008-02-05_18:00:00',: The latest time edge as ccyy-mm-dd_hh:mn:ss
&record6,7,8
```

Edit all the domain setting according with your own experiment. You may pay special attention on NESTIX and NESTJX, which is described ~~in the~~in the section Description of Namelist Variables for details).

```
&record9

use_for = '4DVAR',  ; used for 3D-Var, default
;     num_slots_past and num_slots_ahead are used ONLY for FGAT and 4DVAR:
num_slots_past   = 3, ; the number of time slots before time_analysis
num_slots_ahead  = 3, ; the number of time slots after time_analysis
```

To run OBSPROC, type

```
> obsproc.exe >&! obsproc.out
```

Once `obsproc.exe` has completed successfully, you will see 7 observation data files:

```
obs_gts_2008-02-05_12:00:00.4DVAR
obs_gts_2008-02-05_13:00:00.4DVAR
obs_gts_2008-02-05_14:00:00.4DVAR
obs_gts_2008-02-05_15:00:00.4DVAR
```

```
obs_gts_2008-02-05_16:00:00.4DVAR
obs_gts_2008-02-05_17:00:00.4DVAR
obs_gts_2008-02-05_18:00:00.4DVAR
```

They are the input observation files to WRF 4D-Var. You can also use "`MAP_Plot`" to view the geographic distribution of different observations at different time slots.

Running WRFDA

a. Download Test Data

The WRFDA system requires three input files to run:

a) A WRF *first guess and boudary* input files output from either WPS/real (cold-start)

or WRF forecast (warm-start)

b) Observations (in ASCII format, PREBUFR or BUFR for radiance)

c) A background error statistics file (containing background error covariance)

The following table summarizes the above info:

Input Data	*Format*	*Created By*
First Guess	NETCDF	WRF Preprocessing System (WPS) and real.exe or WRF
Observations	ASCII (PREPBUFR also possible)	Observation Preprocessor (OBSPROC)
Background Error Statistics	Binary	WRFDA gen_be utility /Default CV3

In the test case, you will store data in a directory defined by the environment variable `$DAT_DIR`. This directory can be at any location and it should have read access. Type

```
> setenv DAT_DIR your_choice_of_dat_dir
```

Here, "`your_choice_of_dat_dir`" is the directory where the WRFDA input data is stored. Create this directory if it does not exist, and type

```
> cd $DAT_DIR
```

Download the test data for a "Tutorial" case valid at 12 UTC 5th February 2008 from http://www.mmm.ucar.edu/wrf/users/wrfda/download/testdata.html

Once you have downloaded "WRFDAV3.2-testdata.tar.gz" file to $DAT_DIR, extract it by typing

```
> gunzip WRFDAV3.2-testdata.tar.gz
> tar -xvf WRFDAV3.2-testdata.tar
```

Now you should find the following three sub-directories/files under "$DAT_DIR"

```
ob/2008020512/ob.2008020512.gz   #  Observation data in "little_r" format
rc/2008020512/wrfinput_d01       #  First guess file
rc/2008020512/wrfbdy_d01         #  lateral boundary file
be/be.dat                        #  Background error file
......
```

You should first go through the section "Running Observation Preprocessor (OBSPROC)" and have a WRF-3D-Var-ready observation file (obs_gts_2008-02-05_12:00:00.3DVAR) generated in your OBSPROC working directory. You could then copy or move obs_gts_2008-02-05_12:00:00.3DVAR to be in $DAT_DIR/ob/2008020512/ob.ascii.

If you want to try 4D-Var, please go through the section "Running Observation Preprocessor (OBSPROC)" and have the WRF-4D-Var-ready observation files (obs_gts_2008-02-05_12:00:00.4DVAR,……) . You could copy or move the observation files to $DAT_DIR/ob using following commands:

```
> mv obs_gts_2008-02-05_12:00:00.4DVAR   $DAT_DIR/ob/2008020512/ob.ascii+
> mv obs_gts_2008-02-05_13:00:00.4DVAR   $DAT_DIR/ob/2008020513/ob.ascii
> mv obs_gts_2008-02-05_14:00:00.4DVAR   $DAT_DIR/ob/2008020514/ob.ascii
> mv obs_gts_2008-02-05_15:00:00.4DVAR   $DAT_DIR/ob/2008020515/ob.ascii
> mv obs_gts_2008-02-05_16:00:00.4DVAR   $DAT_DIR/ob/2008020516/ob.ascii
> mv obs_gts_2008-02-05_17:00:00.4DVAR   $DAT_DIR/ob/2008020517/ob.ascii
> mv obs_gts_2008-02-05_18:00:00.4DVAR   $DAT_DIR/ob/2008020518/ob.ascii-
```

At this point you have three of the input files (first guess, observation and background error statistics files in directory $DAT_DIR) required to run WRFDA, and have successfully downloaded and compiled the WRFDA code. If this is correct, you are ready to learn how to run WRFDA.

b. Run the Case—3D-Var

The data for this case is valid at 12 UTC 5th February 2008. The first guess comes from the NCEP FNL (Final) Operational Global Analysis data, passed through the WRF-WPS and *real* programs.

To run WRF 3D-Var, first create and cd to a working directory, for example, WRFDA/var/test/tutorial, and then follow the steps below:

```
> cd WRFDA/var/test/tutorial
> ln -sf WRFDA/run/LANDUSE.TBL ./LANDUSE.TBL
> ln -sf $DAT_DIR/rc/2008020512/wrfinput_d01 ./fg (link first guess file as fg)
> ln -sf WRFDA/var/obsproc/obs_gts_2008-02-05_12:00:00.3DVAR ./ob.ascii (link OBSPROC
processed observation file as ob.ascii)
> ln -sf $DAT_DIR/be/be.dat ./be.dat (link background error statistics as be.dat)
> ln -sf WRFDA/var/da/da_wrfvar.exe ./da_wrfvar.exe (link executable)
```

We will begin by editing the file, `namelist.input`, which is a very basic namelist.input for running the tutorial test case is shown below and provided as `WRFDA/var/test/tutorial/namelist.input`. Only the time and domain settings need to be specified in this case, if we are using the default settings provided in `WRFDA/Registry/Registry.wrfvar`)

```
&wrfvar1
print_detail_grad=false,
/
&wrfvar2
/
&wrfvar3
/
&wrfvar4
/
&wrfvar5
/
&wrfvar6
/
&wrfvar7
/
&wrfvar8
/
&wrfvar9
/
&wrfvar10
/
&wrfvar11
/
&wrfvar12
/
&wrfvar13
/
&wrfvar14
/
&wrfvar15
/
&wrfvar16
/
&wrfvar17
/
&wrfvar18
analysis_date="2008-02-05_12:00:00.0000",
/
&wrfvar19
/
&wrfvar20
/
&wrfvar21
time_window_min="2008-02-05_11:00:00.0000",
/
&wrfvar22
time_window_max="2008-02-05_13:00:00.0000",
/
&wrfvar23
/
&time_control
start_year=2008,
start_month=02,
start_day=05,
start_hour=12,
end_year=2008,
end_month=02,
end_day=05,
end_hour=12,
/
&dfi_control
/
&domains
e_we=90,
e_sn=60,
e_vert=41,
dx=60000,
dy=60000,
/
&physics
```

```
        mp_physics=3,
        ra_lw_physics=1,
        ra_sw_physics=1,
        radt=60,
        sf_sfclay_physics=1,
        sf_surface_physics=1,
        bl_pbl_physics=1,
        cu_physics=1,
        cudt=5,
        num_soil_layers=5,  (IMPORTANT: it's essential to make sure the setting
        here is consistent with the number in your first guess file)
        mp_zero_out=2,
        co2tf=0,
        /
        &fdda
        /
        &dynamics
        /
        &bdy_control
        /
        &grib2
        /
        &namelist_quilt
        /

> da_wrfvar.exe >&! wrfda.log
```

The file `wrfda.log` (or `rsl.out.0000` if run in distributed-memory mode) contains important WRFDA runtime log information. Always check the log after a WRFDA run:

```
***  VARIATIONAL ANALYSIS ***
 DYNAMICS OPTION: Eulerian Mass Coordinate
 WRF NUMBER OF TILES =   1
Set up observations (ob)

Using ASCII format observation input

 scan obs ascii
 end scan obs ascii
Observation summary
   ob time  1
      sound                 85 global,      85 local
      synop                531 global,     525 local
      pilot                 84 global,      84 local
      satem                 78 global,      78 local
      geoamv               736 global,     719 local
      polaramv               0 global,       0 local
      airep                132 global,     131 local
      gpspw                183 global,     183 local
      gpsrf                  0 global,       0 local
      metar               1043 global,    1037 local
      ships                 86 global,      82 local
      ssmi_rv                0 global,       0 local
      ssmi_tb                0 global,       0 local
      ssmt1                  0 global,       0 local
      ssmt2                  0 global,       0 local
      qscat                  0 global,       0 local
      profiler              61 global,      61 local
      buoy                 216 global,     216 local
      bogus                  0 global,       0 local
      pseudo                 0 global,       0 local
      radar                  0 global,       0 local
      radiance               0 global,       0 local
      airs retrieval         0 global,       0 local
      sonde_sfc             85 global,      85 local
      mtgirs                 0 global,       0 local
      tamdar                 0 global,       0 local

Set up background errors for regional application
   WRF-Var dry control variables are:psi, chi_u, t_u and psfc
   Humidity control variable is q/qsg
   Using the averaged regression coefficients for unbalanced part

Vertical truncation for psi    =  15(  99.00%)

Vertical truncation for chi_u  =  20(  99.00%)
```

```
Vertical truncation for t_u    =  29(  99.00%)

Vertical truncation for rh     =  22(  99.00%)


Calculate innovation vector (iv)

Minimize cost function using CG method
For this run cost function diagnostics will not be written

Starting outer iteration :   1
Starting cost function:  2.28356084D+04, Gradient=  2.23656955D+02
For this outer iteration gradient target is:        2.23656955D+00
------------------------------------------------------------
Iter      Gradient             Step
  1      1.82455068D+02      7.47025772D-02
  2      1.64971618D+02      8.05531077D-02
  3      1.13694365D+02      7.22382618D-02
  4      7.87359568D+01      7.51905761D-02
  5      5.71607218D+01      7.94572516D-02
  6      4.18746777D+01      8.30731280D-02
  7      2.95722963D+01      6.13223951D-02
  8      2.34205172D+01      9.05920463D-02
  9      1.63772518D+01      6.48090044D-02
 10      1.09735524D+01      7.71148550D-02
 11      8.22748934D+00      8.81041046D-02
 12      5.65846963D+00      7.89528133D-02
 13      4.15664769D+00      7.45589721D-02
 14      3.16925808D+00      8.35300020D-02
------------------------------------------------------------

Inner iteration stopped after   15 iterations

Final:  15 iter, J= 1.76436785D+04, g= 2.06098421D+00
------------------------------------------------------------

Diagnostics
   Final cost function J       =     17643.68

   Total number of obs.        =    26726
   Final value of J            =     17643.67853
   Final value of Jo           =     15284.64894
   Final value of Jb           =      2359.02958
   Final value of Jc           =         0.00000
   Final value of Je           =         0.00000
   Final value of Jp           =         0.00000
   Final J / total num_obs     =         0.66017
   Jb factor used(1)           =         1.00000
   Jb factor used(2)           =         1.00000
   Jb factor used(3)           =         1.00000
   Jb factor used(4)           =         1.00000
   Jb factor used(5)           =         1.00000
   Jb factor used              =         1.00000
   Je factor used              =         1.00000
   VarBC factor used           =         1.00000


 *** WRF-Var completed successfully ***
```

A file called `namelist.output` (which contains the complete namelist settings) will be generated after a successful da_wrfvar.exe run. The settings appearing in `namelist.output`, but not specified in your `namelist.input`, are the default values from `WRFDA/Registry/Registry.wrfvar`.

After successful completion of job, `wrfvar_output` (the WRFDA analysis file, i.e. the new initial condition for WRF) should appear in the working directory along with a number of diagnostic files. Various text diagnostics output files will be explained in the next section (WRFDA Diagnostics).

In order to understand the role of various important WRFDA options, try re-running WRFDA by changing different namelist options. Such as making WRFDA convergence criteria more stringent. This is achieved by reducing the value of the convergence criteria "`EPS`" to e.g. 0.0001 by adding "`EPS=0.0001`" in the `namelist.input` record `&wrfvar6`. See section (WRFDA additional exercises) for more namelist options

c. Run the Case—4D-Var

To run WRF 4D-Var, first create and cd to a working directory, for example, `WRFDA/var/test/4dvar`; next assuming that we are using the C-shell, set the working directories for the three WRF 4D-Var components WRFDA, WRFNL and WRFPLUS thusly

```
> setenv WRFDA_DIR /ptmp/$user/WRFDA
> setenv WRFNL_DIR /ptmp/$user/WRFNL
> setenv WRFPLUS_DIR /ptmp/$user/WRFPLUS
```

Assume the analysis date is 2008020512 and the test data directories are:

```
> setenv DATA_DIR /ptmp/$user/DATA
> ls -lr $DATA_DIR
ob/2008020512
ob/2008020513
ob/2008020514
ob/2008020515
ob/2008020516
ob/2008020517
ob/2008020518
rc/2008020512
be
```

Note: Currently, WRF 4D-Var can only run with the observation data processed by OBSPROC, and cannot work with PREPBUFR format data; Although WRF-4DVar is able to assimilate satellite radiance BUFR data, but this capability is still under testing.

Assume the working directory is:

```
> setenv WORK_DIR $WRFDA_DIR/var/test/4dvar
```

Then follow the steps below:

1) Link the executables.

```
> cd $WORK_DIR
> ln -fs $WRFDA_DIR/var/da/da_wrfvar.exe .
> cd $WORK_DIR/nl
> ln -fs $WRFNL_DIR/main/wrf.exe .
> cd $WORK_DIR/ad
> ln -fs $WRFPLUS_DIR/main/wrfplus.exe .
> cd $WORK_DIR/tl
> ln -fs $WRFPLUS_DIR/main/wrfplus.exe .
```

2) Link the observational data, first guess and BE. (Currently, only LITTLE_R formatted observational data is supported in 4D-Var, PREPBUFR observational data is not supported)

```
> cd $WORK_DIR
> ln -fs $DATA_DIR/ob/2008020512/ob.ascii+ ob01.ascii
> ln -fs $DATA_DIR/ob/2008020513/ob.ascii  ob02.ascii
> ln -fs $DATA_DIR/ob/2008020514/ob.ascii  ob03.ascii
> ln -fs $DATA_DIR/ob/2008020515/ob.ascii  ob04.ascii
> ln -fs $DATA_DIR/ob/2008020516/ob.ascii  ob05.ascii
> ln -fs $DATA_DIR/ob/2008020517/ob.ascii  ob06.ascii
> ln -fs $DATA_DIR/ob/2008020518/ob.ascii- ob07.ascii

> ln -fs $DATA_DIR/rc/2008020512/wrfinput_d01 .
> ln -fs $DATA_DIR/rc/2008020512/wrfbdy_d01 .
> ln -fs wrfinput_d01 fg
> ln -fs wrfinput_d01 fg01

> ln -fs $DATA_DIR/be/be.dat .
```

3) Establish the miscellaneous links.

```
> cd $WORK_DIR
> ln -fs nl/nl_d01_2008-02-05_13:00:00 fg02
> ln -fs nl/nl_d01_2008-02-05_14:00:00 fg03
> ln -fs nl/nl_d01_2008-02-05_15:00:00 fg04
> ln -fs nl/nl_d01_2008-02-05_16:00:00 fg05
> ln -fs nl/nl_d01_2008-02-05_17:00:00 fg06
> ln -fs nl/nl_d01_2008-02-05_18:00:00 fg07

> ln -fs ad/ad_d01_2008-02-05_12:00:00 gr01

> ln -fs tl/tl_d01_2008-02-05_13:00:00 tl02
> ln -fs tl/tl_d01_2008-02-05_14:00:00 tl03
> ln -fs tl/tl_d01_2008-02-05_15:00:00 tl04
> ln -fs tl/tl_d01_2008-02-05_16:00:00 tl05
> ln -fs tl/tl_d01_2008-02-05_17:00:00 tl06
> ln -fs tl/tl_d01_2008-02-05_18:00:00 tl07

> cd $WORK_DIR/ad
> ln -fs ../af01 auxinput3_d01_2008-02-05_12:00:00
> ln -fs ../af02 auxinput3_d01_2008-02-05_13:00:00
> ln -fs ../af03 auxinput3_d01_2008-02-05_14:00:00
> ln -fs ../af04 auxinput3_d01_2008-02-05_15:00:00
> ln -fs ../af05 auxinput3_d01_2008-02-05_16:00:00
> ln -fs ../af06 auxinput3_d01_2008-02-05_17:00:00
> ln -fs ../af07 auxinput3_d01_2008-02-05_18:00:00
```

4) Run in single processor mode (serial compilation required for WRFDA, WRFNL and WRFPLUS)

- Edit `$WORK_DIR/namelist.input` to match your experiment settings.
- > cp `$WORK_DIR/nl/namelist.input.serial $WORK_DIR/nl/namelist.input`
- Edit `$WORK_DIR/nl/namelist.input` to match your experiment settings.
- > cp `$WORK_DIR/ad/namelist.input.serial $WORK_DIR/ad/namelist.input`

- > cp $WORK_DIR/tl/namelist.input.serial $WORK_DIR/tl/namelist.input
- Edit $WORK_DIR/ad/namelist.input and $WORK_DIR/tl/namelist.input to match your experiment settings, but only change following variables:

```
&time_control
run_hours=06,
start_year=2008,
start_month=02,
start_day=05,
start_hour=12,
end_year=2008,
end_month=02,
end_day=05,
end_hour=18,
......
&domains
time_step=360,   # NOTE:MUST BE THE SAME WITH WHICH IN
$WORK_DIR/nl/namelist.input
e_we=90,
e_sn=60,
e_vert=41,
dx=60000,
dy=60000,
......

> cd $WORK_DIR
> setenv NUM_PROCS 1
> ./da_wrfvar.exe >&! wrfda.log
```

5) Run with multiple processors with MPMD mode. (dmpar compilation required for WRFDA, WRFNL and WRFPLUS)

- Edit $WORK_DIR/namelist.input to match your experiment settings.
- > cp $WORK_DIR/nl/namelist.input.parallel $WORK_DIR/nl/namelist.input
- Edit $WORK_DIR/nl/namelist.input to match your experiment settings.
- > cp $WORK_DIR/ad/namelist.input.parallel $WORK_DIR/ad/namelist.input
- > cp $WORK_DIR/tl/namelist.input.parallel $WORK_DIR/tl/namelist.input
- Edit $WORK_DIR/ad/namelist.input and $WORK_DIR/tl/namelist.input to match your experiment settings.

Currently, parallel WRF 4D-Var is a MPMD (Multiple Program Multiple Data) application. Because there are so many parallel configurations across the platforms, it is very difficult to define a generic way to run the WRF 4D-Var parallel. As an example, to launch the three WRF 4D-Var executables as a concurrent parallel job on a 16 processor cluster, use:

```
> mpirun –np 4 da_wrfvar.exe: -np 8 ad/wrfplus.exe: -np 4 nl/wrf.exe
```

In the above example, 4 processors are assigned to run WRFDA, 4 processors are assigned to run WRFNL and 8 processors for WRFPLUS due to high computational cost in adjoint code.

The file `wrfda.log` (or `rsl.out.0000` if running in parallel mode) contains important WRF-4DVar runtime log information. Always check the log after a WRF-4DVar run.

Radiance Data Assimilations in WRFDA

This section gives a brief description for various aspects related to radiance assimilation in WRFDA. Each aspect is described mainly from the viewpoint of usage rather than more technical and scientific details, which will appear in separated technical report and scientific paper. Namelist parameters controlling different aspects of radiance assimilation will be detailed in the following sections. It should be noted that this section does not cover general aspects of the WRFDA assimilation. These can be found in other sections of chapter 6 of this users guide or other WRFDA documentation.

a. Running WRFDA with radiances

In addition to the basic input files (`LANDUSE.TBL, fg, ob.ascii, be.dat`) mentioned in "Running WRFDA" section, the following extra files are required for radiances: radiance data in NCEP BUFR format, radiance_info files, `VARBC.in`, RTM (CRTM or RTTOV) coefficient files.

Edit `namelist.input` (Pay special attention to `&wrfvar4, &wrfvar14, &wrfvar21, and &wrfvar22` for radiance-related options. A very basic namelist.input for running the radiance test case is provided as `WRFDA/var/test/radiance/namelist.input`)

```
> ln -sf ${DAT_DIR}/gdas1.t00z.1bamua.tm00.bufr_d   ./amsua.bufr
> ln -sf ${DAT_DIR}/gdas1.t00z.1bamub.tm00.bufr_d   ./amsub.bufr
> ln -sf WRFDA/var/run/radiance_info  ./radiance_info  # (radiance_info
is a directory)
> ln -sf WRFDA/var/run/VARBC.in  ./VARBC.in
(CRTM only)  > ln -sf WRFDA/var/run/crtm_coeffs ./crtm_coeffs
#(crtm_coeffs is a directory)
(RTTOV only) > ln -sf rttov87/rtcoef_rttov7/* .       #   (a list of
rtcoef* files)
```

See the following sections for more details on each aspect.

b. Radiance Data Ingest

Currently, the ingest interface for NCEP BUFR radiance data is implemented in WRFDA. The radiance data are available through NCEP's public ftp server ***ftp://ftp.ncep.noaa.gov/pub/data/nccf/com/gfs/prod/gdas.${yyyymmddhh}*** in near real-time (with 6-hour delay) and can meet requirements both for research purposes and some real-time applications.

So far, WRFDA can read data from the NOAA ATOVS instruments (HIRS, AMSU-A, AMSU-B and MHS), the EOS Aqua instruments (AIRS, AMSU-A) and DMSP instruments (SSMIS). Note that NCEP radiance BUFR files are separated by instrument names

(i.e., each file for one type instrument) and each file contains global radiance (generally converted to brightness temperature) within 6-hour assimilation window from multi-platforms. For running WRFDA, users need to rename NCEP corresponding BUFR files (table 1) to hirs3.bufr (including HIRS data from NOAA-15/16/17), hirs4.bufr (including HIRS data from NOAA-18, METOP-2), amsua.bufr (including AMSU-A data from NOAA-15/16/18, METOP-2), amsub.bufr (including AMSU-B data from NOAA-15/16/17), mhs.bufr (including MHS data from NOAA-18 and METOP-2), airs.bufr (including AIRS and AMSU-A data from EOS-AQUA) and ssmis.bufr (SSMIS data from DMSP-16, AFWA provided) for WRFDA filename convention. Note that airs.bufr file contains not only AIRS data but also AMSU-A, which is collocated with AIRS pixels (1 AMSU-A pixels collocated with 9 AIRS pixels). Users must place these files in the working directory where WRFDA executable is located. It should also be mentioned that WRFDA reads these BUFR radiance files directly without use if any separate pre-processing program is used. All processing of radiance data, such as quality control, thinning and bias correction and so on, is carried out inside WRFDA. This is different from conventional observation assimilation, which requires a pre-processing package (OBSPROC) to generate WRFDA readable ASCII files. For reading the radiance BUFR files, WRFDA must be compiled with the NCEP BUFR library (see ***http://www.nco.ncep.noaa.gov/sib/decoders/BUFRLIB/***).

Table 1: NCEP and WRFDA radiance BUFR file naming convention

NCEP BUFR file names	WRFDA naming convention
gdas1.t00z.1bamua.tm00.bufr_d	*amsua.bufr*
gdas1.t00z.1bamub.tm00.bufr_d	*amsub.bufr*
gdas1.t00z.1bhrs3.tm00.bufr_d	*hirs3.bufr*
gdas1.t00z.1bhrs4.tm00.bufr_d	*hirs4.bufr*
gdas1.t00z.1bmhs.tm00.bufr_d	*mhs.bufr*
gdas1.t00z.airsev.tm00.bufr_d	*airs.bufr*

Namelist parameters are used to control the reading of corresponding BUFR files into WRFDA. For instance, `USE_AMSUAOBS`, `USE_AMSUBOBS`, `USE_HIRS3OBS`, `USE_HIRS4OBS`, `USE_MHSOBS`, `USE_AIRSOBS`, `USE_EOS_AMSUAOBS` and `USE_SSMISOBS` control whether or not the respective file is read. These are logical parameters that are assigned to FALSE by default; therefore they must be set to *true* to read the respective observation file. Also note that these parameters only control whether the data is read, not whether the data included in the files is to be assimilated. This is controlled by other namelist parameters explained in the next section.

NCEP BUFR files downloaded from NCEP's public ftp server ***ftp://ftp.ncep.noaa.gov/pub/data/nccf/com/gfs/prod/gdas.${yyyymmddhh}*** are Fortran-blocked on big-endian machine and can be directly used on big-endian machines (for example, IBM). For most Linux clusters with Intel platforms, users need to first unblock the BUFR files, and then reblock them. The utility for blocking/unblocking is available from ***http://www.nco.ncep.noaa.gov/sib/decoders/BUFRLIB/toc/cwordsh***

c. Radiative Transfer Model

The core component for direct radiance assimilation is to incorporate a radiative transfer model (RTM, should be accurate enough yet fast) into the WRFDA system as one part of observation operators. Two widely used RTMs in NWP community, RTTOV8* (developed by EUMETSAT in Europe), and CRTM (developed by the Joint Center for Satellite Data Assimilation (JCSDA) in US), are already implemented in WRFDA system with a flexible and consistent user interface. Selecting which RTM to be used is controlled by a simple namelist parameter RTM_OPTION (1 for RTTOV, the default, and 2 for CRTM). WRFDA is designed to be able to compile with only one of two RTM libraries or without RTM libraries (for those not interested in radiance assimilation) by the definition of environment variables "CRTM" and "RTTOV" (see Installing WRFDA section).

Both RTMs can calculate radiances for almost all available instruments aboard various satellite platforms in orbit. An important feature of WRFDA design is that all data structures related to radiance assimilation are dynamically allocated during running time according to simple namelist setup. The instruments to be assimilated are controlled at run time by four integer namelist parameters: RTMINIT_NSENSOR (the total number of sensors to be assimilated), RTMINIT_PLATFORM (the platforms IDs array to be assimilated with dimension RTMINIT_NSENSOR, e.g., 1 for NOAA, 9 for EOS, 10 for METOP and 2 for DMSP), RTMINIT_SATID (satellite IDs array) and RTMINIT_SENSOR (sensor IDs array, e.g., 0 for HIRS, 3 for AMSU-A, 4 for AMSU-B, 15 for MHS, 10 for SSMIS, 11 for AIRS). For instance, the configuration for assimilating 12 sensors from 7 satellites (what WRFDA can assimilated currently) will be

```
RTMINIT_NSENSOR = 12 # 5 AMSUA; 3 AMSUB; 2 MHS; 1 AIRS; 1 SSMIS
RTMINIT_PLATFORM = 1,1,1,9,10,          1,1,1,   1,10,     9,   2
RTMINIT_SATID =          15,16,18,2,2,  15,16,17, 18,2,     2,   16
RTMINIT_SENSOR =      3,3,3,3,3,            4,4,4,    15,15,  11,  10
```

The instrument triplets (platform, satellite and sensor ID) in the namelist can be ranked in any order. More detail about the convention of instrument triplet can be found at the tables 2 and 3 in RTTOV8/9 Users Guide (***http://www.metoffice.gov.uk/research/interproj/nwpsaf/rtm/rttov8_ug.pdf*** Or ***http://www.metoffice.gov.uk/research/interproj/nwpsaf/rtm/rttov9_files/users_guide_91_v1.6.pdf***)

CRTM uses a different instrument naming method. A convert routine inside WRFDA is already created to make CRTM use the same instrument triplet as RTTOV such that the user interface remains the same for RTTOV and CRTM.

When running WRFDA with radiance assimilation switched on (RTTOV or CRTM), a set of RTM coefficient files need to be loaded. For RTTOV option, RTTOV coefficient files are to be directly copied or linked under the working directory; for CRTM option,

* Current release is RTTOV9, while there is no plan to incorporate RTTOV9 into WRFDA.

CRTM coefficient files are to be copied or linked to a sub-directory "crtm_coeffs" under the working directory. Only coefficients listed in namelist are needed. Potentially WRFDA can assimilate all sensors as long as the corresponding coefficient files are provided with RTTOV and CRTM. In addition, necessary developments on corresponding data interface, quality control and bias correction are also important to make radiance data assimilated properly. However, a modular design of radiance relevant routines already facilitates much to add more instruments in WRFDA.

RTTOV packages are not distributed with WRFDA due to license and support issues. Users are encouraged to contact the corresponding team for obtaining RTMs. See following links for more information.
http://www.metoffice.gov.uk/research/interproj/nwpsaf/rtm/index.html .
CRTM pakages are now distributed with WRFDA, which locate in the WRFDA/var/external/crtm. Users can still find it on the following link:
ftp://ftp.emc.ncep.noaa.gov/jcsda/CRTM.

d. Channel Selection

Channel selection in WRFDA is controlled by radiance 'info' files located in the sub-directory 'radiance_info' under the working directory. These files are separated by satellites and sensors, e.g., noaa-15-amsua.info, noaa-16-amsub.info, dmsp-16-ssmis.info and so on. An example for 5 channels from noaa-15-amsub.info is shown below. The fourth column is used by WRFDA to control if assimilating corresponding channel. Channels with the value "-1" indicates that the channel is "not assimilated" (channels 1, 2 and 4 in this case), with the value "1" means "assimilated" (channels 3 and 5). The sixth column is used by WRFDA to set the observation error for each channel. Other columns are not used by WRFDA. It should be mentioned that these error values might not necessarily be optimal for your applications; It is user's responsibility to obtain the optimal error statistics for your own applications.

```
 sensor channel IR/MW use idum  varch  polarisation(0:vertical;1:horizontal)
   415    1    1   -1    0  0.5500000000E+01  0.0000000000E+00
   415    2    1   -1    0  0.3750000000E+01  0.0000000000E+00
   415    3    1    1    0  0.3500000000E+01  0.0000000000E+00
   415    4    1   -1    0  0.3200000000E+01  0.0000000000E+00
   415    5    1    1    0  0.2500000000E+01  0.0000000000E+00
```

e. Bias Correction

Satellite radiance is generally considered biased with respect to a reference (e.g., background or analysis field in NWP assimilation) due to system error of observation itself, reference field and RTM. Bias correction is a necessary step prior to assimilating radiance data. In WRFDA, there are two ways of performing bias correction. One is based on

Harris and Kelly (2001) method and is carried out using a set of coefficient files pre-calculated with an off-line statistics package, which will apply to a training dataset for a month-long period. The other is Variational Bias Correction (VarBC). Only VarBC is introduced here and recommended for users because of its relative simplicity in usage.

f. Variational Bias Correction

Getting started with VarBC
To use VarBC, set namelist option `USE_VARBC` to TRUE and have a VARBC.in file in the working directory. VARBC.in is a VarBC setup file in ASCII format. A template is provided with the WRFDA package (WRFDA/var/run/VARBC.in).

Input and Output files
All VarBC input is passed through one single ASCII file called VARBC.in file. Once WRFDA has run with the VarBC option switched on, it will produce a VARBC.out file which looks very much like the VARBC.in file you provided. This output file will then be used as input file for the next assimilation cycle.

Coldstart
Coldstarting means starting the VarBC from scratch i.e. when you do not know the values of the bias parameters.

The Coldstart is a routine in WRFDA. The bias predictor statistics (mean and standard deviation) are computed automatically and will be used to normalize the bias parameters. All coldstarted bias parameters are set to zero, except the first bias parameter (= simple offset), which is set to the mode (=peak) of the distribution of the (uncorrected) innovations for the given channel.

A threshold of number of observations can be set through a namelist option `VARBC_NOBSMIN` (default = 10), under which it is considered that not enough observations are present to keep the Coldstart values (i.e. bias predictor statistics and bias parameter values) for the next cycle. In this case, the next cycle will do another Coldstart.

Background Constraint for the bias parameters
The background constraint controls the inertia you want to impose on the predictors (i.e. the smoothing in the predictor time series). It corresponds to an extra term in the WRFDA cost function.

It is defined through an integer number in the VARBC.in file. This number is related to a number of observations: the bigger the number, the more inertia constraint. If these numbers are set to zero, the predictors can evolve without any constraint.

Scaling factor
The VarBC uses a specific preconditioning, which can be scaled through a namelist option `VARBC_FACTOR` (default = 1.0).

Offline bias correction
The analysis of the VarBC parameters can be performed "offline", i.e. independently from the main WRFDA analysis. No extra code is needed, just set the following MAX_VERT_VAR* namelist variables to be 0, which will disable the standard control variable and only keep the VarBC control variable.

```
MAX_VERT_VAR1=0.0
MAX_VERT_VAR2=0.0
MAX_VERT_VAR3=0.0
MAX_VERT_VAR4=0.0
MAX_VERT_VAR5=0.0
```

Freeze VarBC
In certain circumstances, you might want to keep the VarBC bias parameters constant in time (="frozen"). In this case, the bias correction is read and applied to the innovations, but it is not updated during the minimization. This can easily be achieved by setting the namelist options:

```
USE_VARBC=false
FREEZE_VARBC=true
```

Passive observations
Some observations are useful for preprocessing (e.g. Quality Control, Cloud detection) but you might not want to assimilate them. If you still need to estimate their bias correction, these observations need to go through the VarBC code in the minimization. For this purpose, the VarBC uses a separate threshold on the QC values, called "qc_varbc_bad". This threshold is currently set to the same value as "qc_bad", but can easily be changed to any ad hoc value.

g. Other namelist variables to control radiance assimilation

RAD_MONITORING (30)
Integer array of dimension RTMINIT_NSENSER, where 0 for assimilating mode, 1 for monitoring mode (only calculate innovation).

THINNING
Logical, TRUE will perform thinning on radiance data.

THINNING_MESH (30)
Real array with dimension RTMINIT_NSENSOR, values indicate thinning mesh (in KM) for different sensors.

QC_RAD
Logical, control if perform quality control, always set to TRUE.

WRITE_IV_RAD_ASCII
Logical, control if output Observation minus Background files which are in ASCII format and separated by sensors and processors.

WRITE_OA_RAD_ASCII
Logical, control if output Observation minus Analysis files (including also O minus B) which are ASCII format and separated by sensors and processors.

USE_ERROR_FACTOR_RAD
Logical, controls use of a radiance error tuning factor file “radiance_error.factor”, which is created with empirical values or generated using variational tuning method (Desroziers and Ivanov, 2001)

ONLY_SEA_RAD
Logical, controls whether only assimilating radiance over water.

TIME_WINDOW_MIN
String, e.g., "2007-08-15_03:00:00.0000", start time of assimilation time window

TIME_WINDOW_MAX
String, e.g., "2007-08-15_09:00:00.0000", end time of assimilation time window

CRTM_ATMOSPHERE
Integer, used by CRTM to choose climatology reference profile used above model top (up to 0.01hPa).
0: Invalid (default, use U.S. Standard Atmosphere)
1: Tropical
2: Midlatitude summer
3: Midlatitude winter
4: Subarctic summer
5: Subarctic winter
6: U.S. Standard Atmosphere

USE_ANTCORR (30)
Logical array with dimension RTMINIT_NSENSER, control if performing Antenna Correction in CRTM.

AIRS_WARMEST_FOV
Logical, controls whether using the observation brightness temperature for AIRS Window channel #914 as criteria for GSI thinning.

USE_CRTM_KMATRIX
Logical, controls whether using CRTM K matrix rather than calling CRTM TL and AD routines for gradient calculation.

h. Diagnostics and Monitoring

(1) Monitoring capability within WRFDA.

Run WRFDA with the rad_monitoring namelist parameter in record wrfvar14 in namelist.input.

0 means assimilating mode, innovations (O minus B) are calculated and data are used in minimization.
1 means monitoring mode: innovations are calculated for diagnostics and monitoring. Data are not used in minimization.

Number of rad_monitoring should correspond to number of rtminit_nsensor. If rad_monitoring is not set, then default value of 0 will be used for all sensors.

(2) Outputing radiance diagnostics from WRFDA

Run WRFDA with the following namelist variables in record wrfvar14 in namelist.input.

write_iv_rad_ascii=.true.
to write out (observation-background) and other diagnostics information in plain-text files with prefix inv followed by instrument name and processor id. For example, 01_inv_noaa-17-amsub.0000 (01 is outerloop index, 0000 is processor index)

write_oa_rad_ascii=.true.
to write out (observation-background), (observation-analysis) and other diagnostics information in plain-text files with prefix oma followed by instrument name and processor id. For example, 01_oma_noaa-18-mhs.0001

Each processor writes out information of one instrument in one file in the WRFDA working directory.

(3) Radiance diagnostics data processing

A Fortran90 program is used to collect the 01_inv* or 01_oma* files and write out in netCDF format (one instrument in one file with prefix diags followed by instrument name, analysis date, and suffix .nc)) for easier data viewing, handling and plotting with netCDF utilities and NCL scripts.

(4) Radiance diagnostics plotting

NCL scripts (WRFDA/var/graphics/ncl/plot_rad_diags.ncl and WRFDA/var/graphics/ncl/advance_cymdh.ncl) are used for plotting. The NCL script can be run from a shell script, or run stand-alone with interactive ncl com-

mand (need to edit the NCL script and set the plot options. Also the path of advance_cymdh.ncl, a date advancing script loaded in the main NCL plotting script, may need to be modified).

Step (3) and (4) can be done by running a single ksh script (WRFDA/var/scripts/da_rad_diags.ksh) with proper settings. In addition to the settings of directories and what instruments to plot, there are some useful plotting options, explained below.

export OUT_TYPE=ncgm	*ncgm or pdf* *pdf will be much slower than ncgm and generate huge output if plots are not split. But pdf has higher resolution than ncgm.*
export PLOT_STATS_ONLY=false	*true or false* *true: only statistics of OMB/OMA vs channels and OMB/OMA vs dates will be plotted.* *false: data coverage, scatter plots (before and after bias correction), histograms (before and after bias correction), and statistics will be plotted.*
export PLOT_OPT=sea_only	*all, sea_only, land_only*
export PLOT_QCED=false	*true or false* *true: plot only quality-controlled data* *false: plot all data*
export PLOT_HISTO=false	*true or false: switch for histogram plots*
export PLOT_SCATT=true	*true or false: switch for scatter plots*
export PLOT_EMISS=false	*true or false: switch for emissivity plots*
export PLOT_SPLIT=false	*true or false* *true: one frame in each file* *false: all frames in one file*
export PLOT_CLOUDY=false	*true or false* *true: plot cloudy data. Cloudy data to be plotted are defined by PLOT_CLOUDY_OPT (si or clwp), CLWP_VALUE, SI_VALUE settings.*
export PLOT_CLOUDY_OPT=si	*si or clwp* *clwp: cloud liquid water path from model* *si: scatter index from obs, for amsua, amsub and mhs only*
export CLWP_VALUE=0.2	*only plot points with* *clwp >= clwp_value (when clwp_value > 0)* *clwp > clwp_value (when clwp_value = 0)*
export SI_VALUE=3.0	

(5) evolution of VarBC parameters

NCL scripts (`WRFDA/var/graphics/ncl/plot_rad_varbc_param.ncl` and `WRFDA/var/graphics/ncl/advance_cymdh.ncl`) are used for plotting evolutions of VarBC parameters.

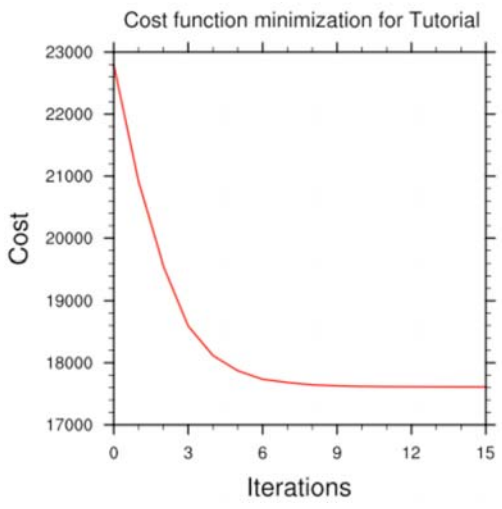
WRFDA Diagnostics

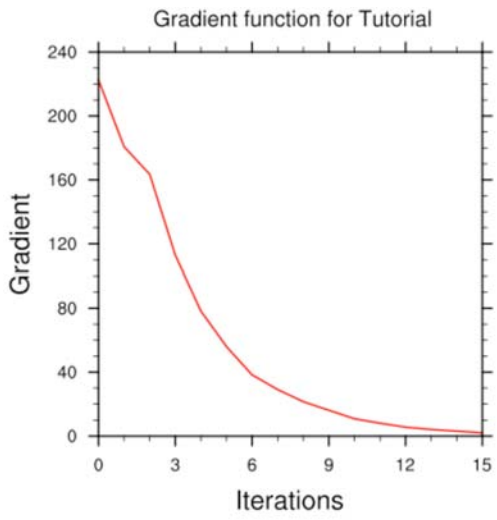
WRFDA produces a number of diagnostic files that contain useful information on how the data assimilation has performed. This section will introduce you to some of these files, and what to look for.

Having run WRFDA, it is important to check a number of output files to see if the assimilation appears sensible. The WRFDA package, which includes lots of useful scripts may be downloaded from http://www.mmm.ucar.edu/wrf/users/wrfda/download/tools.html

The content of some useful diagnostic files are as follows:

`cost_fn` and `grad_fn`: These files hold (in ASCII format) WRFDA cost and gradient function values, respectively, for the first and last iterations. However, if you run with `PRINT_DETAIL_GRAD=true`, these values will be listed for each iteration; this can be helpful for visualization purposes. The NCL script `WRFDA/var/graphcs/ncl/plot_cost_grad_fn.ncl` may be used to plot the content of `cost_fn` and `grad_fn`, if these files are generated with `PRINT_DETAIL_GRAD=true`.





Note: Make sure that you removed first two lines (header) in `cost_fn` and `grad_fn` before you plot. Also, you need to specify the directory name for these two files.

`gts_omb_oma_01`: It contains (in ASCII format) information on all of the observations used by the WRFDA run. Each observation has its observed value, quality flag, observation error, observation minus background (OMB), and observation minus analysis (OMA). This information is very useful for both analysis and forecasts verification purposes.

`namelist.input`: This is the WRFDA input namelist file, which contains all the user defined non-default options. Any namelist defined options that do not appear in this file, should have their names checked against values in `WRFDA/Registry/Registry.wrfvar`.

`namelist.output`: A consolidated list of all the namelist options used.

`rsl*`: Files containing information of standard WRFDA output from individual processors when multiple processors are used. It contains host of information on number of observations, minimization, timings etc. Additional diagnostics may be printed in these files by including various "print" WRFDA namelist options. To learn more about these additional "print" options, search "print_" string in `WRFDA/Registry/Registry.wrfvar`.

`statistics`: Text file containing OMB (OI), OMA (OA) statistics (minimum, maximum, mean and standard deviation) for each observation type and variable. This information is very useful in diagnosing how WRFDA has used different components of the observing system. Also contained are the analysis minus background (A-B) statistics i.e. statistics of the analysis increments for each model variable at each model level. This information is very useful in checking the range of analysis increment values found in the analysis, and where they are in the WRF-model grid space.

The WRFDA analysis file is `wrfvar_output`. It is in WRF (NetCDF) format. It will become the input file "wrfinput_d01" of any subsequent WRF runs after lateral boundary and/or low boundary conditions are updated by another WRFDA utility (See section "Updating WRF boundary conditions").

A NCL script `WRFDA/var/graphics/ncl/WRF-Var_plot.ncl`, is provided for plotting. You need to specify the `analsyis_file` name, its full path etc. Please see the in-line comments in the script for details.

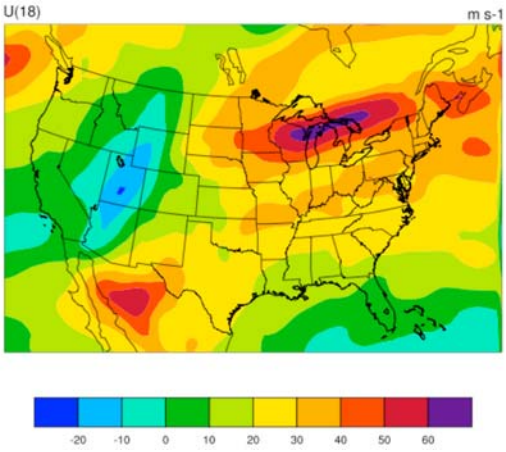
As an example, if you are aiming to display U-component of the analysis at level 18, execute the following command after modifying the script "`WRFDA/var/graphcs/ncl/WRF-Var_plot.ncl`", make sure the following piece of codes are uncommented:

```
var = "U"
fg = first_guess->U
an = analysis->U
plot_data = an
```

When you execute the following command from `WRFDA/var/graphics/ncl`.

```
> ncl WRF-Var_plot.ncl
```

The plot should look like:



You may change the variable name, level etc in this script to display the variable of your choice at the desired eta level.

Take time to look through the text output files to ensure you understand how WRFDA works. For example,

How closely has WRFDA fitted individual observation types? Look at the `statistics` file to compare the O-B and O-A statistics.

How big are the analysis increments? Again, look in the `statistics` file to see minimum/maximum values of A-B for each variable at various levels. It will give you a feel for the impact of input observation data you assimilated via WRFDA by modifying the input analysis first guess.

How long did WRFDA take to converge? Does it really converge? You will get the answers of all these questions by looking into `rsl`-files, as it indicates the number of iterations taken by WRFDA to converge. If this is the same as the maximum number of iterations specified in the namelist (`NTMAX`) or its default value (=200) set in `WRFDA/Registry/Registry.wrfvar`, then it means that the analysis solution did not converge. If so, you may like to increase the value of "`NTMAX`" and rerun your case to ensure that the convergence is achieved. On the other hand, a normal WRFDA run should usually converge within 100 iterations. If it still doesn't converge in 200 iterations, that means there might be some problem in the observations or first guess.

A good visual way of seeing the impact of assimilation of observations is to plot the analysis increments (i.e. analysis minus first guess difference). There are many different graphics packages used (e.g. RIP4, NCL, GRADS etc) that can do this. The plot of level 18 theta increments below was produced using the particular NCL script. This script is located at `WRFDA/var/graphcs/ncl/WRF-Var_plot.ncl`.

You need to modify this script to fix the full path for `first_guess & analysis` files. You may also like to modify the display level by setting "`kl`" and the name of the variable to display by setting "`var`". Further details are given in this script.

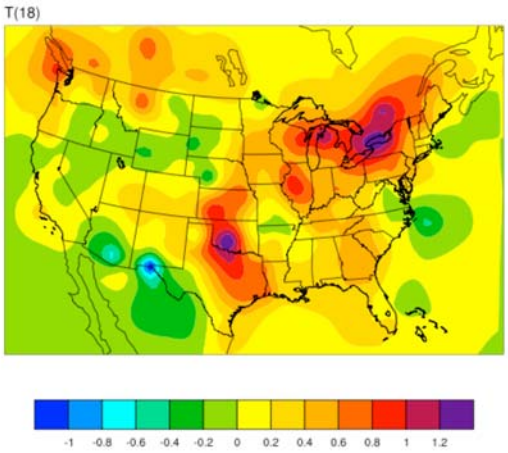
If you are aiming to display increment of potential temperature at level 18, after modifying `WRFDA/var/graphcs/ncl/WRF-Var_plot.ncl` suitably, make sure following pieces of codes are uncommented:

```
var = "T"
fg = first_guess->T ;Theta- 300
an = analysis->T    ;Theta- 300
plot_data = an - fg
```

When you execute the following command from "`WRFDA/var/graphics/ncl`".

```
> ncl WRF-Var_plot.ncl
```

The plot created will looks as follows:



Note: Larger analysis increments indicate a larger data impact in the corresponding region of the domain.

Updating WRF boundary conditions

Before running NWP forecast using the WRF-model with WRFDA analysis, the values and tendencies for each of predicted variables for the first time period in the lateral boundary condition file for domain-1 (wrfbdy_d01) must be updated to be consistent with the new WRFDA initial condition (analysis). This is absolutely essential. Moreover, in the cycling run mode (warm-start), the low boundary in the WRFDA analysis file also need to be updated based on the information of the wrfinput file generated by WPS/real.exe at the analysis time. So there are three input files: WRFDA analysis, wrfin-

put and wrfbdy files from WPS/real.exe, and a namelist file: `param.in` for running da_`update_bc.exe` for domain-1.

For the nested domains, domain-2, domain-3…, the lateral boundaries are provided by their parent domains, so no lateral boundary update needed for these domains, But the low boundaries in each of the nested domains' WRFDA analysis files are still need to be updated. In these cases, you must set the namelist variable, domain_id > 1 (default is 1 for domain-1), and no wrfbdy_d01file need to be provided to the namelist variable: wrf_bdy_file.

This procedure is performed by the WRFDA utility called `da_updated_bc.exe`.

Note: Make sure that you have `da_update_bc.exe` in `WRFDA/var/build` directory. This executable should be created when you compiled WRFDA code,

To run da_update_`bc.exe`, follow the steps below:

```
> cd WRFDA/var/test/update_bc
> cp -p $DAT_DIR/rc/2008020512/wrfbdy_d01 ./wrfbdy_d01 (IMPORTANT:
make a copy of wrfbdy_d01 as the wrf_bdy_file will be overwritten
by da_update_bc.exe)
> vi parame.in
&control_param
 wrfvar_output_file = './wrfvar_output'
 wrf_bdy_file       = './wrfbdy_d01'
 wrf_input          = '$DAT_DIR/rc/2008020512/wrfinput_d01'

 cycling = .false. (set to .true. if WRFDA first guess comes from
a previous WRF forecast.)
 debug   = .true.
 low_bdy_only = .false.
 update_lsm = .false.
/
> ln -sf WRFDA/var/da/da_update_bc.exe ./da_update_bc.exe
> ./da_updatebc.exe
```

At this stage, you should have the files `wrfvar_output` and `wrfbdy_d01` in your WRFDA working directory. They are the WRFDA updated initial condition and boundary condition for any subsequent WRF model runs. To use, just link a copy of `wrfvar_output` and `wrfbdy_d01` to `wrfinput_d01` and `wrfbdy_d01`, respectively, in your WRF working directory.

Running gen_be

Starting with WRFDA version 3.1, the users have two choices to define the background error covariance (BE). We call them CV3 and CV5 respectively. Both are applied to the same set of the control variables, stream function, unbalanced potential velocity, unbalanced temperature, unbalanced surface pressure, and pseudo relative humidity. With CV3, the control variables are in physical space while with CV5 the control variables are in eigenvector space. So the major differences between these two kinds of BE are the ver-

tical covariance. CV3 uses the vertical recursive filter to model the vertical covariance but CV5 uses the empirical orthogonal function (EOF) to represent the vertical covariance. The recursive filters to model the horizontal covariance are also different in these two BEs. We have not conducted the systematic comparison of the analyses based on these two BEs. However, CV3 (a BE file provided with our WRFDA system) is a global BE and can be used for any regional domains while CV5 is a domain-dependent BE, which should be generated based in the forecasts data from the same domain. At this time, it is hard to tell which BE is better; the impact on analysis may be varying case by case.

CV3 is the NCEP background error covariance, it is estimated in grid space by what has become known as the NMC method (Parrish and Derber 1992) . The statistics are estimated with the differences of 24 and 48-hour GFS forecasts with T170 resolution valid at the same time for 357 cases distributed over a period of one year. Both the amplitudes and the scales of the background error have to be tuned to represent the forecast error in the guess fields. The statistics that project multivariate relations among variables are also derived from the NMC method.

The variance of each variable and the variance of its second derivative are used to estimate its horizontal scales. For example, the horizontal scales of the stream function can be estimated from the variance of the vorticity and stream function.

The vertical scales are estimated with the vertical correlation of each variable. A table is built to cover the range of vertical scales for the variables. The table is then used to find the scales in vertical grid units. The filter profile and the vertical correlation are fitted locally. The scale of the best fit from the table is assigned as the scale of the variable at that vertical level for each latitude. Note that the vertical scales are locally defined so that the negative correlation further away in the vertical direction is not included.

Theoretically, CV3 BE is a generic background error statistics file can be used for any case. It is quite straightforward to use CV3 in your own case. To use CV3 BE file in your case, just set `cv_options=3` in `$wrfvar7` and the `be.dat` is located in `WRFDA/var/run/be.dat.cv3`.

To use CV5 background error covariance, it is necessary to generate your domain-specific background error statistics with the gen_be utility. The background error statistics file supplied with the tutorial test case can NOT be used for your applications other than the tutorial case

The Fortran main programs for gen_be can be found in `WRFDA/var/gen_be`. The executables of gen_be should be created after you have compiled the WRFDA code (as described earlier). The scripts to run these codes are in `WRFDA/var/scripts/gen_be`.

The input data for gen_be are WRF forecasts, which are used to generate model perturbations, used as a proxy for estimates of forecast error. For the NMC-method, the model perturbations are differences between forecasts (e.g. T+24 minus T+12 is typical for re-

gional applications, T+48 minus T+24 for global) valid at the same time. Climatological estimates of background error may then be obtained by averaging such forecast differences over a period of time (e.g. one month). Given input from an ensemble prediction system (EPS), the inputs are the ensemble forecasts, and the model perturbations created are the transformed ensemble perturbations. The gen_be code has been designed to work with either forecast difference, or ensemble-based perturbations. The former is illustrated in this tutorial example.

It is important to include forecast differences from at least 00Z and 12Z through the period, to remove the diurnal cycle (i.e. do not run gen_be using just 00Z or 12Z model perturbations alone).

The inputs to gen_be are NetCDF WRF forecast output ("wrfout") files at specified forecast ranges. To avoid unnecessary large single data files, it is assumed that all forecast ranges are output to separate files. For example, if we wish to calculate BE statistics using the NMC-method with (T+24)-(T+12) forecast differences (default for regional) then by setting the WRF `namelist.input` options `history_interval=720`, and `frames_per_outfile=1` we get the necessary output datasets. Then the forecast output files should be arranged as follows: directory name is the forecast initial time, time info in the file name is the forecast valid time. `2008020512/wrfout_d01_2008-02-06_00:00:00` mean a 12-hour forecast valid at `2008020600` initialized at `2008020512`.

Example dataset for a test case (90 x 60 x 41 gridpoints) can be downloaded from http://www.mmm.ucar.edu/wrf/users/wrfda/download/testdata.html, untar the `gen_be_forecasts_20080205.tar.gz`, you will have:

```
>ls $FC_DIR

-rw-r--r--  1   users  11556492 2008020512/wrfout_d01_2008-02-06_00:00:00
-rw-r--r--  1   users  11556492 2008020512/wrfout_d01_2008-02-06_12:00:00
-rw-r--r--  1   users  11556492 2008020600/wrfout_d01_2008-02-06_12:00:00
-rw-r--r--  1   users  11556492 2008020600/wrfout_d01_2008-02-07_00:00:00
-rw-r--r--  1   users  11556492 2008020612/wrfout_d01_2008-02-07_00:00:00
-rw-r--r--  1   users  11556492 2008020612/wrfout_d01_2008-02-07_12:00:00
```

In the above example, only 1 day (12Z 05 Feb to 12Z 06 Feb. 2002) of forecasts, every 12 hours are supplied to `gen_be_wrapper` to estimate forecast error covariance. It is only for demonstration. The minimum number of forecasts required depends on the application, number of grid points, etc. Month-long (or longer) datasets are typical for the NMC-method. Generally, at least 1-month dataset should be used.

Under `WRFDA/var/scripts/gen_be`, `gen_be_wrapper.ksh` is used to generate the BE data, following variables need to be set to fit your case:

```
export WRFVAR_DIR=/users/noname/work/code/trunk/phoenix_g95_opt/WRFDA
export START_DATE=2008020612  # the first perturbation valid date
export END_DATE=2008020700    # the last perturbation valid date
export NUM_LEVELS=40          # e_vert - 1
export BIN_TYPE=5
export FC_DIR=/users/noname/work/exps/friendlies/expt/fc # where wrf forecasts are
export RUN_DIR=/users/noname/work/exps/friendlies/gen_be${BIN_TYPE}
```

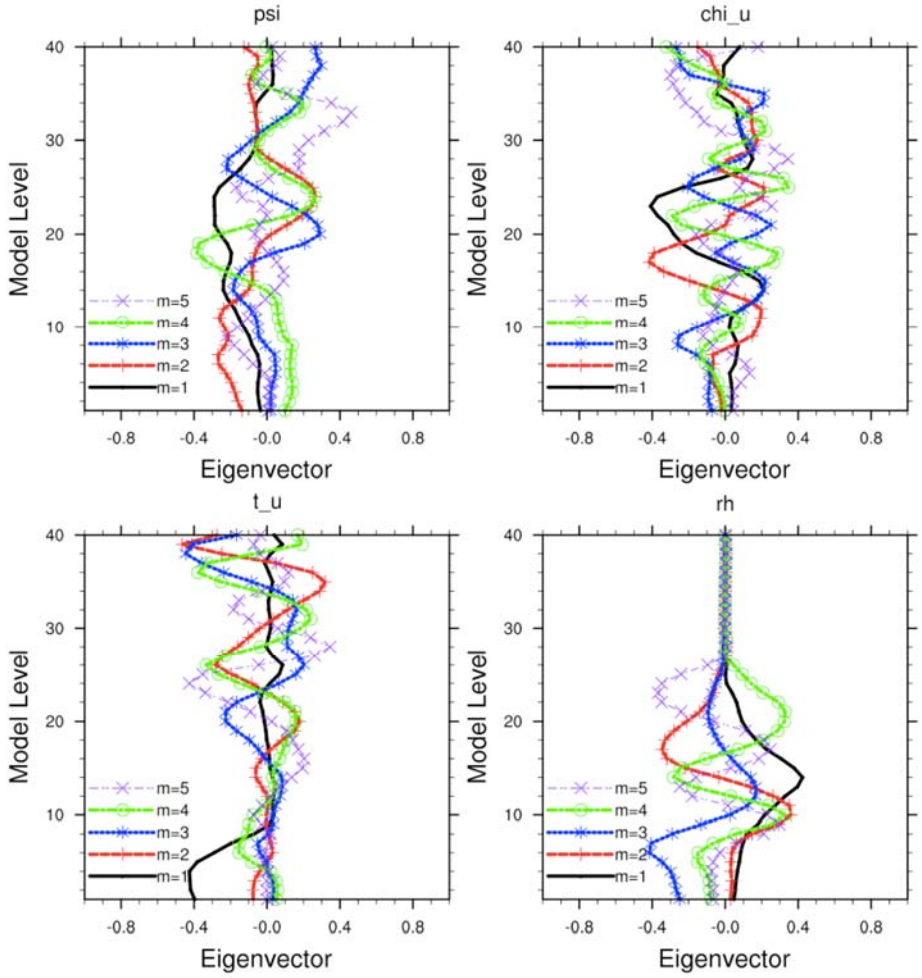
Note: The START_DATE and END_DATE are perturbation valid dates. As show in the forecast list above, when you have 24-hour and 12-hour forecasts initialized at 2008020512 through 2008020612, the first and final forecast difference valid dates are 2008020612 and 2008020700 respectively.

Note: The forecast dataset should be located in `$FC_DIR`. Then type:

```
> gen_be_wrapper.ksh
```

Once `gen_be_wrapper.ksh` runs completed, the `be.dat` can be found under `$RUN_DIR` directory.

To get a clear idea about what are included in `be.dat`, the script `gen_be_plot_wrapper.ksh` may be used to plot various data in `be.dat` such as:



Additional WRFDA Exercises:

(a) Single Observation response in WRFDA:

With the single observation test, you may get the ideas of how the background and observation error statistics working in the model variable space. Single observation test is done in WRFDA by setting `num_pseudo=1` along with other pre-specified values in record `&wrfvar15` and `&wrfvar19` of `namelist.input`,

With the settings shown below, WRFDA generates a single observation with pre-specified *innovation* (Observation – First Guess) value at desired location e.g. at (in terms of grid coordinate) 23x23, level 14 for "U" observation with error characteristics 1 m/s, innovation size = 1.0 m/s.

```
&wrfvar15
num_pseudo = 1,
pseudo_x = 23.0,
pseudo_y = 23.0,
pseudo_z = 14.0,
pseudo_err = 1.0,
pseudo_val = 1.0,
/
&wrfvar19
pseudo_var = "u", (Note: pseudo_var can be u, v, t, p, q.
If pseudo_var is q, then the reasonable values of pseudo_err and
pseudo_val are 0.001)
/
```

Note: You may like to repeat this exercise for other observations like temperature ("t"), pressure "p", specific humidity "q" etc.

(b) Response of BE length scaling parameter:

Run single observation test with following additional parameters in record `&wrfvar7` of namelist.input

```
&wrfvar7
len_scaling1 = 0.5, # reduce psi length scale by 50%
len_scaling2 = 0.5, # reduce chi_u length scale by 50%
len_scaling3 = 0.5, # reduce T length scale by 50%
len_scaling4 = 0.5, # reduce q length scale by 50%
len_scaling5 = 0.5, # reduce Ps length scale by 50%
/
```

Note: You may like to try the response of an individual variable by setting one parameter at one time. See the spread of analysis increment.

(c) Response of changing BE variance:

Run single observation test with following additional parameters in record `&wrfvar7` of namelist.input

```
&wrfvar7
var_scaling1 = 0.25,   # reduce psi variance by 75%
var_scaling2 = 0.25,   # reduce chi_u variance by 75%
var_scaling3 = 0.25,   # reduce T variance by 75%
var_scaling4 = 0.25,   # reduce q variance by 75%
var_scaling5 = 0.25,   # reduce Ps variance by 75%
/
```

Note: You may like to try the response of individual variable by setting one parameter at one time. See the magnitude of analysis increments.

(d) Response of convergence criteria:

Run tutorial case with

```
&wrfvar6
eps = 0.0001,
/
```

You may like to compare various diagnostics with earlier run.

(e) Response of outer loop on minimization:

Run tutorial case with

```
&wrfvar6
max_ext_its = 2,
/
```

With this setting "outer loop" for the minimization procedure will get activated. You may like to compare various diagnostics with earlier run.

Note: Maximum permissible value for "`MAX_EXT_ITS`" is 10

(f) Response of suppressing particular types of data in WRFDA:

The types of observations that WRFDA gets to use actually depend on what is included in the observation file and the WRFDA namelist settings. For example, if you have SYNOP data in the observation file, you can suppress its usage in WRFDA by setting `use_synopobs=false` in record `&wrfvar4` of `namelist.input`. It is OK if there is no SYNOP data in the observation file and `use_synopobs=true`.

Turning on and off of certain types of observations are widely used for assessing impact of observations on data assimilations.

Note: It is important to go through the default "use_*" settings in record `&wrfvar4` in `WRFDA/Registry/Registry.wrfvar` to know what observations are activated in default.

Hybrid Data Assimilation in WRFDA

The WRFDA system also includes a hybrid data assimilation technique, which is based on the existing 3DVAR. The difference between hybrid and 3DVAR schemes is that 3DVAR relies solely on a static covariance model to specify the background errors, while the hybrid system uses a combination of 3DVAR static error covariances and ensemble-estimated error covariances to incorporate a flow-dependent estimate of the background error statistics. Please refer to Wang et al. (2008a,b) for a detailed description of the methodology used in the WRF hybrid system. The following section will give a brief introduction of various aspects of using the hybrid system.

a. Source Code

There are three executables that are used in the hybrid system. If you have successfully compiled the WRFDA system, you will see the following:

```
WRFDA/var/build/gen_be_ensmean.exe
WRFDA/var/build/gen_be_ep2.exe
WRFDA/var/build/da_wrfvar.exe
```

gen_be_ensmean.exe is used to calculate the ensemble mean, while gen_be_ep2.exe is used to calculate the ensemble perturbations. As with 3DVAR/4DVAR, da_wrfvar.exe is the main WRFDA program. However, in this case, da_wrfvar.exe will run in the hybrid mode.

b. Running The Hybrid System

The procedure is the same as running 3DVAR/4DVAR with the exception of some extra input files and namelist settings. The basic input files for WRFDA are LANDUSE.TBL, ob.ascii or ob.bufr (depending on which observation format you use), and be.dat (static background errors). Additional input files required by the hybrid are a single ensemble mean file (used as the fg for the hybrid application) and a set of ensemble perturbation files (used to represent flow-dependent background errors).

Before the hybrid application can be started, a set of initial ensemble members must be prepared. These ensembles can be obtained from other ensemble model outputs or you can generate them yourself, for example, adding random noise to the initial conditions at a previous time and integrating each member to the desired time. Once you have the initial ensembles, the ensemble mean and perturbations can be calculated following the steps below.

1) Calculate ensemble mean

Copy or link the ensemble forecasts to your working directory. In this example, the time is 2006102712.

```
< ln -sf /wrfhelp/DATA/VAR/Hybrid/fc/2006102712.e0* .
```

Next, copy the directory that contains two template files (ensemble mean and variance files) to your working directory. In this case, the directory name is 2006102712, which contains the template ensemble mean file (wrfout_d01_2006-10-28_00:00:00) and the template variance file (wrfout_d01_2006-10-28_00:00:00.vari). These template files will be overwritten by the program that calculates the ensemble mean and variance as discussed below.

```
< cp -r /wrfhelp/DATA/VAR/Hybrid/fc/2006102712 .
```

Edit gen_be_ensmean_nl.nl (or copy it from /wrfhelp/DATA/VAR/Hybrid/gen_be_ensmean_nl.nl). You will need to set the following information in this script as follows:

< vi gen_be_ensmean_nl.nl

```
&gen_be_ensmean_nl
directory = './2006102712'
filename = 'wrfout_d01_2006-10-28_00:00:00'
num_members = 10
nv = 7
cv = 'U', 'V', 'W', 'PH', 'T', 'MU', 'QVAPOR'
/
```

Here,
“directory” is the folder you just copied,
“filename” is the name of the ensemble mean file,
“num_members” is the number of ensemble members you are using,
“nv” is the number of variables, which must be consistent with the next “cv” option, and
“cv” is the name of variables used in the hybrid system.

Next, link gen_be_ensmean.exe to your working directory and run it.

```
< ln -sf  WRFDA/var/build/gen_be_ensmean.exe .
< ./ gen_be_ensmean.exe
```

Check the output files.

2006102712/wrfout_d01_2006-10-28_00:00:00 is the ensemble mean

2006102712/wrfout_d01_2006-10-28_00:00:00.vari is the ensemble variance

2) Calculate ensemble perturbations

Create another sub-directory in which you will be working to create ensemble perturbations.

```
< mkdir -p 2006102800/ep
< cd 2006102800/ep
```

Next, run gen_be_ep2.exe.

gen_be_ep2.exe requires four command-line arguments (DATE, NUM_MEMBER, DIRECTORY, FILENAME) as shown below:

```
< ln –sf WRFDA/var/build/gen_be_ep2.exe   .
< ./gen_be_ep2.exe    2006102800   10
../../2006102712    wrfout_d01_2006-10-28_00:00:00
```

Check the output files.

A list of binary files will be created under the 2006102800/ep directory. Among them, tmp.e* are temporary scratch files that can be removed.

3) Run WRFDA in hybrid mode

In your hybrid working directory, link all the necessary files and directories as follows:

```
< ln -fs 2006102800/ep ./ep (ensemble perturbation files should be under
the ep subdirectory)
< ln -fs 2006102712/wrfout_d01_2006-10-28_00:00:00 ./fg  (first guess is
the ensemble mean)
< ln -fs WRFDA/run/LANDUSE.TBL .
< ln -fs /wrfhelp/DATA/VAR/Hybrid/ob/2006102800/ob.ascii ./ob.ascii (or
ob.bufr)
< ln -fs /wrfhelp/DATA/VAR/Hybrid/be/be.dat ./be.dat
< ln –fs WRFDA/var/build/da_wrfvar.exe .
< cp /wrfhelp/DATA/VAR/Hybrid/namelist.input .
```

Edit namelist.input and pay special attention to the following hybrid-related settings:

```
&wrfvar7
je_factor = 2.0
/
&wrfvar16
ensdim_alpha = 10
alphacv_method = 2
alpha_corr_type=3
alpha_corr_scale = 1500.0
alpha_std_dev=1.000
/
```

Next, run hybrid in serial mode (recommended for initial testing of the hybrid system), or in parallel mode

```
< ./da_wrfvar.exe >&! wrfda.log
```

Check the output files.

The output file lists are the same as when you run WRF 3D-Var.

c. Hybrid namelist options

1) je_factor : ensemble covariance weighting factor. This factor controls the weighting component of ensemble and static covariances. The corresponding jb_factor = je_factor/(je_factor - 1).
2) ensdim_alpha: the number of ensemble members. Hybrid mode is activated when ensdim_alpha is larger than zero.
3) alphacv_method: 1=perturbations in control variable space ("psi","chi_u","t_u","rh","ps_u"); 2=perturbations in model space ("u","v","t","q","ps"). Option 2 is extensively tested and recommended to use.
4) alpha_corr_type: correlation function. 1=Exponential; 2=SOAR; 3=Gaussian.
5) alpha_corr_scale: hybrid covariance localization scale in km unit. Default value is 1500.
6) alpha_std_dev: alpha standard deviation. Default value is 1.0

Description of Namelist Variables

- WRFDA namelist variables.

Variable Names	Default Value	Description
&wrfvar1		
write_increments	false	.true.: write out a binary analysis increment file
var4d	false	.true.: 4D-Var mode
multi_inc	0	> 0: multi-incremental run
var4d_coupling	2	1: var4d_coupling_disk_linear, 2: var4d_coupling_disk_simul
print_detail_radar	false	print_detail_xxx: output extra (sometimes can be too many) diagnostics for debugging; not recommended to turn them on for production runs
print_detail_xa	false	
print_detail_xb	false	
print_detail_obs	false	
print_detail_grad	false	the purpose of print_detail_grad is changed as of V3.1. .true.: to print out detailed gradient of each observation type at each iteration and write out detailed cost function and gradient into files called cost_fn and grad_fn
check_max_iv_print	true	obsolete (only used by Radar)
&wrfvar2		
analysis_accu	900	seconds, if time difference between namelist setting (analysis_date) and date info read in from first guess is larger than analysis_accu, WRFDA will issue a warning message ("=======> Wrong xb

		time found???"), but won't abort.
calc_w_increment	false	.true.: the increment of the vertical velocity W will be diagnosed based on the increments of other fields. If there is information of the W from observations assimilated, such as the Radar radial velocity, the W increments are always computed, no matter calc_w_increment=true. or .false. .false.: the increment of the vertical velocity W is zero if no W information assimilated.
dt_cloud_model	false	Not used
&wrfvar3		
fg_format	1	1: fg_format_wrf_arw_regional (default) 2: fg_format_wrf_nmm_regional 3: fg_format_wrf_arw_global 4: fg_format_kma_global
ob_format	2	1: ob_format_bufr (NCEP PREPBUFR), read in data from ob.bufr (not fully tested) 2: ob_format_ascii (output from obsproc), read in data from ob.ascii (default) 3: ob_format_madis (not tested)
num_fgat_time	1	1: 3DVar > 1: number of time slots for FGAT and 4DVAR
&wrfvar4		
thin_conv	true	for ob_format=1 (NCEP PREPBUFR) only. thining is mandatory for ob_format=1 as time-duplicate data are "thinned" within thinning routine, however, thin_conv can be set to .false. for debugging purpose.
thin_mesh_conv	20. (max_instruments)	for ob_format=1 (NCEP PREPBUFR) only. km, each observation type can set its thinning mesh and the index/order follows the definition in WRFDA/var/da/da_control/da_control.f90
use_synopobs	true	use_xxxobs - .true.: assimilate xxx obs if available .false.: not assimilate xxx obs even available
use_shipsobs	true	
use_metarobs	true	
use_soundobs	true	
use_pilotobs	true	
use_airepobs	true	
use_geoamvobs	true	
use_polaramvobs	true	

use_bogusobs	true	
use_buoyobs	true	
use_profilerobs	true	
use_satemobs	true	
use_gpspwobs	true	
use_gpsrefobs	true	
use_qscatobs	true	
use_radarobs	false	
use_radar_rv	false	
use_radar_rf	false	
use_airsretobs	true	

; use_hirs2obs, use_hirs3obs, use_hirs4obs, use_mhsobs
; use_msuobs, use_amsuaobs, use_amsubobs, use_airsobs,
; use_eos_amsuaobs, use_hsbobs, use_ssmisobs are
; radiance-related variables that only control if reading
; in corresponding BUFR files into WRFDA or not, but
; do not control if assimilate the data or not.
; Some more variables have to be set in &wrfvar14 in order
; to assimilate radiance data.

use_hirs2obs	fasle	.true.: to read in data from hirs2.bufr
use_hirs3obs	false	.true.: to read in data from hirs3.bufr
use_hirs4obs	false	.true.: to read in data from hirs4.bufr
use_mhsobs	false	.true.: to read in data from mhs.bufr
use_msuobs	false	.true.: to read in data from msu.bufr
use_amsuaobs	false	.true.: to read in data from amsua.bufr
use_amsubobs	false	.true.: to read in data from amsub.bufr
use_airsobs	false	.true.: to read in data from airs.bufr
use_eos_amsuaobs	false	.true.: to read in data from airs.bufr
use_hsbobs	false	.true.: to read in data from hsb.bufr
use_ssmisobs	false	.true.: to read in data from ssmis.bufr
use_obs_errfac	false	.true.: apply obs error tuning factors if errfac.dat is available for conventional data only

&wrfvar5

check_max_iv	true	.true.: reject the observations whose innovations (O-B) are larger than a maximum value defined as a multiple of the observation error for each observation. i.e., inv > (obs_error*factor) --> fails_error_max; the default maximum value is 5 times the observation error ; the factor of 5 can be

		changed through max_error_* settings.
max_error_t	5.0	maximum check_max_iv error check factor for t
max_error_uv	5.0	maximum check_max_iv error check factor for u and v
max_error_pw	5.0	maximum check_max_iv error check factor for precipitable water
max_error_ref	5.0	maximum check_max_iv error check factor for gps refractivity
max_error_q	5.0	maximum check_max_iv error check factor for specific humidity
max_error_p	5.0	maximum check_max_iv error check factor for pressure
max_error_thickness		maximum check_max_iv error check factor for thickness
max_error_rv		maximum check_max_iv error check factor for radar radial velocity
max_error_rf		maximum check_max_iv error check factor for radar reflectivity
&wrfvar6		
max_ext_its	1	number of outer loops
ntmax	200	maximum number of iterations in an inner loop
eps	0.01 (max_ext_its)	minimization convergence criterion (used dimension: max_ext_its); minimization stops when the norm of the gradient of the cost function gradient is reduced by a factor of eps. inner minimization stops either when the criterion is met or when inner iterations reach ntmax.
&wrfvar7		
cv_options	5	3: NCEP Background Error model 5: NCAR Background Error model (default)
as1(3)	-1.0	tuning factors for variance, horizontal and vertical scales for control variable 1 = stream function. For cv_options=3 only. The actual default values are 0.25, 1.0, 1.5.
as2(3)	-1.0	tuning factors for variance, horizontal and vertical scales for control variable 2 - unbalanced potential velocity. For cv_options=3 only. The actual default values are 0.25, 1.0, 1.5.
as3(3)	-1.0	tuning factors for variance, horizontal and vertical scales for control variable 3 - unbalanced temperature. For cv_options=3 only. The actual default values are 0.25, 1.0, 1.5.

as4(3)	-1.0	tuning factors for variance, horizontal and vertical scales for control variable 4 - pseudo relative humidity. For cv_options=3 only. The actual default values are 0.25, 1.0, 1.5.
as5(3)	-1.0	tuning factors for variance, horizontal and vertical scales for control variable 5 - unbalanced surface pressure. For cv_options=3 only. The actual default values are 0.25, 1.0, 1.5.
rf_passes	6	number of passes of recursive filter.
var_scaling1	1.0	tuning factor of background error covariance for control variable 1 - stream function. For cv_options=5 only.
var_scaling2	1.0	tuning factor of background error covariance for control variable 2 - unbalanced velocity potential. For cv_options=5 only.
var_scaling3	1.0	tuning factor of background error covariance for control variable 3 - unbalanced temperature. For cv_options=5 only.
var_scaling4	1.0	tuning factor of background error covariance for control variable 4 - pseudo relative humidity. For cv_options=5 only.
var_scaling5	1.0	tuning factor of background error covariance for control variable 5 - unbalanced surface pressure. For cv_options=5 only.
len_scaling1	1.0	tuning factor of scale-length for stream function. For cv_options=5 only.
len_scaling2	1.0	tuning factor of scale-length for unbalanced velocity potential. For cv_options=5 only.
len_scaling3	1.0	tuning factor of scale-length for unbalanced temperature. For cv_options=5 only.
len_scaling4	1.0	tuning factor of scale-length for pseudo relative humidity. For cv_options=5 only.
len_scaling5	1.0	tuning factor of scale-length for unbalanced surface pressure. For cv_options=5 only.
je_factor	1.0	ensemble covariance weighting factor
&wrfvar8 ;not used		
&wrfvar9		for program tracing. trace_use=.true. gives additional performance diagnostics (calling tree, local routine timings, overall routine timings, memory usage) It does not change results, but does add runtime overhead.
stdout	6	unit number for standard output
stderr	0	unit number for error output

trace_unit	7	Unit number for tracing output note that units 10 and 9 are reserved for reading namelist.input and writing namelist.output respectively.
trace_pe	0	Currently, statistics are always calculated for all processors, and output by processor 0.
trace_repeat_head	10	the number of times any trace statement will produce output for any particular routine. This stops overwhelming trace output when a routine is called multiple times. Once this limit is reached a 'going quiet' message is written to the trace file, and no more output is produced from the routine, though statistics are still gathered.
trace_repeat_body	10	see trace_repeat_head description
trace_max_depth	30	define the deepest level to which tracing writes output
trace_use	true	.true.: activate tracing
trace_use_frequent	false	
trace_use_dull	false	
trace_memory	true	.true.: calculate allocated memory using a mallinfo call. On some platforms (Cray and Mac), mallinfo is not available and no memory monitoring can be done.
trace_all_pes	false	.true.: tracing is output for all pes. As stated in trace_pe, this does not change processor statistics.
trace_csv	true	.true.: tracing statistics are written to a xxxx.csv file in CSV format
use_html	true	.true.: tracing and error reporting routines will include HTML tags.
warnings_are_fatal	false	.true.: warning messages that would normally allow the program to continue are treated as fatal errors.

&wrfvar10 ; for code developer
&wrfvar11

cv_options_hum	1	do not change
check_rh		0 --> No supersaturation check after minimization. 1 --> supersaturation (rh> 100%) and minimum rh (rh<10%) check, and make the local adjustment of q. 2 --> supersaturation (rh> 95%) and minimum rh (rh<11%) check and make the multi-level q adjustment under the constraint of conserved column integrated water vapor
sfc_assi_options	1	1 --> surface observations will be assimilated based on the lowest model level first guess. Obser-

		vations are not used when the height difference of the elevation of the observing site and the lowest model level height is larger than 100m. 2 --> surface observations will be assimilated based on surface similarity theory in PBL. Innovations are computed based on 10-m wind, 2-m temperature and 2-m moisture.
calculate_cg_cost_fn	false	the purpose of calculate_cg_cost_fn is changed. use print_detail_grad=.true. to dump cost function and gradient of each iteration to cost_fn and grad_fn. conjugate gradient algorithm does not require the computation of cost function at every iteration during minimization..true.: cost function is printed out and is directly derived from the gradient using the fully linear properties inside the inner-loop..false.: Only the initial and final cost functions are computed
lat_stats_option	false	do not change
&wrfvar12		
balance_type	1	obsolete
&wrfvar13		
vert_corr	2	do not change
vertical_ip	0	obsolete
vert_evalue	1	do not change
max_vert_var1	99.0	specify the maximum truncation value (in percentage) to explain the variance of stream function in eigenvector decomposition
max_vert_var2	99.0	specify the maximum truncation value (in percentage) to explain the variance of unbalanced potential velocity in eigenvector decomposition
max_vert_var3	99.0	specify the maximum truncation value (in percentage) to explain the variance of the unbalanced temperature in eigenvector decomposition
max_vert_var4	99.0	specify the maximum truncation value (percentage) to explain the variance of pseudo relative humidity in eigenvector decomposition
max_vert_var5	99.0	for unbalanced surface pressure, it should be a non-zero positive numer. set max_vert_var5=0.0 only for offline VarBC applications.

&wrfvar14

the following 4 variables (rtminit_nsensor, rtminit_platform, rtminit_satid, rtminit_sensor) to-

gether control what sensors to be assimilated.

rtminit_nsensor	1	total number of sensors to be assimilated
rtminit_platform	-1 (max_instruments)	platforms IDs array (used dimension: rtminit_nsensor); e.g., 1 for NOAA, 9 for EOS, 10 for METOP and 2 for DMSP
rtminit_satid	-1.0 (max_instruments)	satellite IDs array (used dimension: rtminit_nsensor)
rtminit_sensor	-1.0 (max_instruments)	sensor IDs array (used dimension: rtminit_nsensor); e.g., 0 for HIRS, 3 for AMSU-A, 4 for AMSU-B, 15 for MHS, 10 for SSMIS, 11 for AIRS
rad_monitoring	0 (max_instruments)	integer array (used dimension: rtminit_nsensor); 0: assimilating mode; 1: monitoring mode (only calculate innovations)
thinning_mesh	60.0 (max_instruments)	real array (used dimension: rtminit_nsensor); specify thinning mesh size (in KM) for different sensors.
thinning	false	.true.: perform thinning on radiance data
qc_rad	true	.true.: perform quality control. always .true.
write_iv_rad_ascii	false	.true.: output radiance Observation minus Background files, which are in ASCII format and separated by sensors and processors.
write_oa_rad_ascii	false	.true.: output radiance Observation minus Analysis files (Observation minus Background information is also included), which are in ASCII format and separated by sensors and processors.
use_error_factor_rad	false	.true.: use a radiance error tuning factor file "radiance_error.factor", which can be created with empirical values or generated using variational tuning method (Desroziers and Ivanov, 2001)
use_antcorr	false (max_instruments)	.true.: perform Antenna Correction in CRTM
rtm_option	1	what RTM (Radiative Transfer Model) to use 1: RTTOV (WRFDA needs to compile with RTTOV) 2: CRTM (WRFDA needs to compile with CRTM)
only_sea_rad	false	.true.: assimilate radiance over water only
use_varbc	false	.true.: perform Variational Bias Correction. A parameter file in ASCII format called VARBC.in (a template is provided with the

		source code tar ball) is required.
freeze_varbc	false	.true: together with use_varbc=.false., keep the VarBC bias parameters constant in time. In this case, the bias correction is read and applied to the innovations, but it is not updated during the minimization.
varbc_factor	1.0	for scaling the VarBC preconditioning
varbc_nobsmin	10	defines the minimum number of observations required for the computation of the predictor statistics during the first assimilation cycle. If there are not enough data (according to "VARBC_NOBSMIN") on the first cycle, the next cycle will perform a coldstart again.
airs_warmest_fov	false	.true.: uses the observation brightness temperature forAIRS Window channel #914 as criterion for GSI thinning (with a higher amplitude than the distance from the observation location to the nearest grid point).
crtm_atmosphere	0	climatology reference profile used above model top for CRTM Radiative Transfer Model (up to 0.01hPa 0: Invalid (default, use U.S. Standard Atmosphere) 1: Tropical 2: Midlatitude summer 3: Midlatitude winter 4: Subarctic summer 5: Subarctic winter 6: U.S. Standard Atmosphere
use_crtm_kmatrix	false	.true. use CRTM K matrix rather than calling CRTM TL and AD routines for gradient calculation, which reduces runtime noticeably.

&wrfvar15 (needs to be set together with &wrfvar19)

num_pseudo	0	Set the number of pseudo observations, either 0 or 1 (single ob)
pseudo_x	1.0	Set the x-position (I) of the OBS in unit of grid-point.
pseudo_y	1.0	Set the y-position (J) of the OBS in unit of grid-point.
pseudo_z	1.0	Set the z-position (K) of OBS with the vertical level index, in bottom-up order.
pseudo_val	1.0	Set the innovation of the ob; wind in m/s, pressure in Pa, temperature in K, specific humidity in kg/kg

pseudo_err	1.0	set the error of the pseudo ob. Unit the same as pseudo_val.; if pseudo_var="q", pseudo_err=0.001 is more reasonable.

&wrfvar16 (for hybrid WRFDA/ensemble)

alphacv_method	2	1: ensemble perturbations in control variable space 2: ensemble perturbations in model variable space
ensdim_alpha	0	ensemble size
alpha_corr_type	3	1: alpha_corr_type_exp 2: alpha_corr_type_soar 3: alpha_corr_type_gaussian (default)
alpha_corr_scale	1500.0	km

&wrfvar17

analysis_type	“3D-VAR”	"3D-VAR": 3D-VAR mode (default); "QC-OBS": 3D-VAR mode plus extra filtered_obs output; "VERIFY": verification mode. WRFDA resets check_max_iv=.false. and ntmax=0; "RANDOMCV": for creating ensemble perturbations

&wrfvar18 (needs to set &wrfvar21 and &wrfvar22 as well if ob_format=1 and/or radiances are used)

analysis_date	“2002-08-03_00:00:00.0000”	specify the analysis time. It should be consistent with the first guess time. However, if time difference between analysis_date and date info read in from first guess is larger than analysis_accu, WRFDA will issue a warning message ("=======> Wrong xb time found???"), but won't abort.

&wrfvar19 (needs to be set together with &wrfvar15)

pseudo_var	“t”	Set the name of the OBS variable: 'u' = X-direction component of wind, 'v' = Y-direction component of wind, 't' = Temperature, 'p' = Prerssure, 'q' = Specific humidity "pw": total precipitable water "ref": refractivity "ztd": zenith total delay

&wrfvar20

documentation_url	“http://www.mmm.ucar.edu/people/wrfhelp/wrfvar/code/trunk”	

&wrfvar21

time_window_min	"2002-08-02_21:00:00.0000"	start time of assimilation time window used for ob_format=1 and radiances to select observations inside the defined time_window. Note: Start from V3.1, this variable is also used for ob_format=2 to double-check if the obs are within the specified time window.

&wrfvar22

time_window_max	"2002-08-03_03:00:00.0000"	end time of assimilation time window used for ob_format=1 and radiances to select observations inside the defined time_window. Note: Start from V3.1, this variable is also used for ob_format=2 to double-check if the obs are within the specified time window.

&wrfvar23 (settings related to the 4D-Var penalty term option, which controls the high-frequency gravity waves using a digital filter)

jcdfi_use	false	.true.: Include JcDF term in cost function. .False.: Ignore JcDF term in cost function.
jcdfi_io	false	.true.: Read JcDF output from WRF+. Even jcdfi_use= false. Used for diagnosis. .False.: Ignore the JcDF output from WRF+
jcdfi_tauc	10800	seconds, filter time window second.
jcdfi_gama	1.0	Scaling number used to tune the weight of JcDF term
jcdfi_error_wind	3.0	m/s, wind error used in JcDF
jcdfi_error_t	1.0	K, temperature error used in JcDF
jcdfi_error_q	0.001	kg/kg, specific humidity error used in JcDF
jcdfi_error_mu	1000.	Pa, perturbation pressure (mu) error used in JcDF

OBSPROC namelist variables.

Variable Names	Description
&record1	
obs_gts_filename	name and path of decoded observation file
fg_format	'MM5' for MM5 application, 'WRF' for WRF application
obserr.txt	name and path of observational error file
first_guess_file	name and path of the first guess file
&record2	
time_window_min	The earliest time edge as ccyy-mm-dd_hh:mn:ss

time_analysis	The analysis time as ccyy-mm-dd_hh:mn:ss
time_window_max	The latest time edge as ccyy-mm-dd_hh:mn:ss ** Note : Only observations between [time_window_min, time_window_max] will kept.

&record3

max_number_of_obs	Maximum number of observations to be loaded, ie in domain and time window, this is independent of the number of obs actually read.
fatal_if_exceed_max_obs	.TRUE.: will stop when more than max_number_of_obs are loaded .FALSE.: will process the first max_number_of_obs loaded observations.

&record4

qc_test_vert_consistency	.TRUE. will perform a vertical consistency quality control check on sounding
qc_test_convective_adj	.TRUE. will perform a convective adjustment quality control check on sounding
qc_test_above_lid	.TRUE. will flag the observation above model lid
remove_above_lid	.TRUE. will remove the observation above model lid
domain_check_h	.TRUE. will discard the observations outside the domain
Thining_SATOB	.FALSE.: no thinning for SATOB data. .TRUE.: thinning procedure applied to SATOB data.
Thining_SSMI	.FALSE.: no thinning for SSMI data. .TRUE.: thinning procedure applied to SSMI data.
Thining_QSCAT	.FALSE.: no thinning for SATOB data. .TRUE.: thinning procedure applied to SSMI data.

&record5

print_gts_read	TRUE. will write diagnostic on the decoded obs reading in file obs_gts_read.diag
print_gpspw_read	.TRUE. will write diagnostic on the gpsppw obs reading in file obs_gpspw_read.diag
print_recoverp	.TRUE. will write diagnostic on the obs pressure recovery in file obs_recover_pressure.diag
print_duplicate_loc	.TRUE. will write diagnostic on space duplicate removal in file obs_duplicate_loc.diag
print_duplicate_time	.TRUE. will write diagnostic on time duplicate removal in file obs_duplicate_time.diag
print_recoverh	.TRUE will write diagnostic on the obs height recovery in file obs_recover_height.diag
print_qc_vert	.TRUE will write diagnostic on the vertical consistency check in file obs_qc1.diag
print_qc_conv	.TRUE will write diagnostic on the convective adjustment check in file obs_qc1.diag

print_qc_lid	.TRUE. will write diagnostic on the above model lid height check in file obs_qc2.diag
print_uncomplete	.TRUE. will write diagnostic on the uncompleted obs removal in file obs_uncomplete.diag
user_defined_area	.TRUE.: read in the record6: x_left, x_right, y_top, y_bottom, .FALSE.: not read in the record6.

&record6

x_left	West border of sub-domain, not used
x_right	East border of sub-domain, not used
y_bottom	South border of sub-domain, not used
y_top	North border of sub-domain, not used
ptop	Reference pressure at model top
ps0	Reference sea level pressure
base_pres	Same as ps0. User must set either ps0 or base_pres.
ts0	Mean sea level temperature
base_temp	Same as ts0. User must set either ts0 or base_temp.
tlp	Temperature lapse rate
base_lapse	Same as tlp. User must set either tlp or base_lapse.
pis0	Tropopause pressure, the default = 20000.0 Pa
base_tropo_pres	Same as pis0. User must set either pis0 or base_tropo_pres
tis0	Isothermal temperature above tropopause (K), the default = 215 K.
base_start_temp	Same as tis0. User must set either tis0 or base_start_temp.

&record7

IPROJ	Map projection (0 = Cylindrical Equidistance, 1 = Lambert Conformal, 2 = Polar stereographic, 3 = Mercator)
PHIC	Central latitude of the domain
XLONC	Central longitude of the domain
TRUELAT1	True latitude 1
TRUELAT2	True latitude 2
MOAD_CEN_LAT	The central latitude for the Mother Of All Domains
STANDARD_LON	The standard longitude (Y-direction) of the working domain.

&record8

IDD	Domain ID (1=< ID =< MAXNES), Only the observations geographically located on that domain will be processed. For WRF application with XLONC /= STANDARD_LON, set IDD=2, otherwise set 1.
MAXNES	Maximum numbe of domains as needed.
NESTIX	The I(y)-direction dimension for each of the domains
NESTJX	The J(x)-direction dimension for each of the domains

DIS	The grid size for each of the domains. For WRF application, always set NESTIX(1),NESTJX(1), and DIS(1) based on the infomation in wrfinput.
NUMC	The mother domain ID number for each of the domains
NESTI	The I location in its mother domain of the nest domain's low left corner -- point (1,1)
NESTI	The J location in its mother domain of the nest domain's low left corner -- point (1,1). For WRF application, NUMC(1), NESTI(1), and NESTJ(1) are always set to be 1.

&record9

prep-bufr_output_filename	Name of the prebufr OBS file.
prep-bufr_table_filename	'prepbufr_table_filename' ; not change
output_ob_format	output 1, prebufr OBS file only; 2, ASCII OBS file only; 3, Both prebufr and ASCII OBS files.
use_for	'3DVAR' obs file, same as before, default 'FGAT ' obs files for FGAT '4DVAR' obs files for 4DVAR
num_slots_past	the number of time slots before time_analysis
num_slots_ahead	the number of time slots after time_analysis
write_synop	If keep synop obs in obs_gts (ASCII) files.
write_ship	If keep ship obs in obs_gts (ASCII) files.
write_metar	If keep metar obs in obs_gts (ASCII) files.
write_buoy	If keep buoy obs in obs_gts (ASCII) files.
write_pilot	If keep pilot obs in obs_gts (ASCII) files.
write_sound	If keep sound obs in obs_gts (ASCII) files.
write_amdar	If keep amdar obs in obs_gts (ASCII) files.
write_satem	If keep satem obs in obs_gts (ASCII) files.
write_satob	If keep satob obs in obs_gts (ASCII) files.
write_airep	If keep airep obs in obs_gts (ASCII) files.
write_gpspw	If keep gpspw obs in obs_gts (ASCII) files.
write_gpsztd	If keep gpsztd obs in obs_gts (ASCII) files.
write_gpsref	If keep gpsref obs in obs_gts (ASCII) files.
write_gpseph	If keep gpseph obs in obs_gts (ASCII) files.
write_ssmt1	If keep ssmt1 obs in obs_gts (ASCII) files.
write_ssmt2	If keep ssmt2 obs in obs_gts (ASCII) files.
write_ssmi	If keep ssmi obs in obs_gts (ASCII) files.
write_tovs	If keep tovs obs in obs_gts (ASCII) files.
write_qscat	If keep qscat obs in obs_gts (ASCII) files.

`write_profl`	If keep profile obs in obs_gts (ASCII) files.
`write_bogus`	If keep bogus obs in obs_gts (ASCII) files.
`write_airs`	If keep airs obs in obs_gts (ASCII) files.

Chapter 7: Objective Analysis (OBSGRID)

Table of Contents

Introduction

The goal of objective analysis in meteorological modeling is to improve meteorological analyses (the *first guess*) on the mesoscale grid by incorporating information from observations. Traditionally, these observations have been "direct" observations of temperature, humidity, and wind from surface and radiosonde reports. As remote sensing techniques come of age, more and more "indirect" observations are available for researchers and operational modelers. Effective use of these indirect observations for objective analysis is not a trivial task. Methods commonly employed for indirect observations include three-dimensional or four-dimensional variational techniques ("3DVAR" and "4DVAR", respectively), which can be used for direct observations as well.

This chapter discusses the objective analysis program, OBSGRID. Discussion of variational techniques (*WRF-Var*) can be found in Chapter 6 of this User's Guide.

The analyses input to OBSGRID as the first guess are analyses output from the METGRID part of the WPS package (*see Chapter 3 of this User's Guide for details regarding the WPS package*).

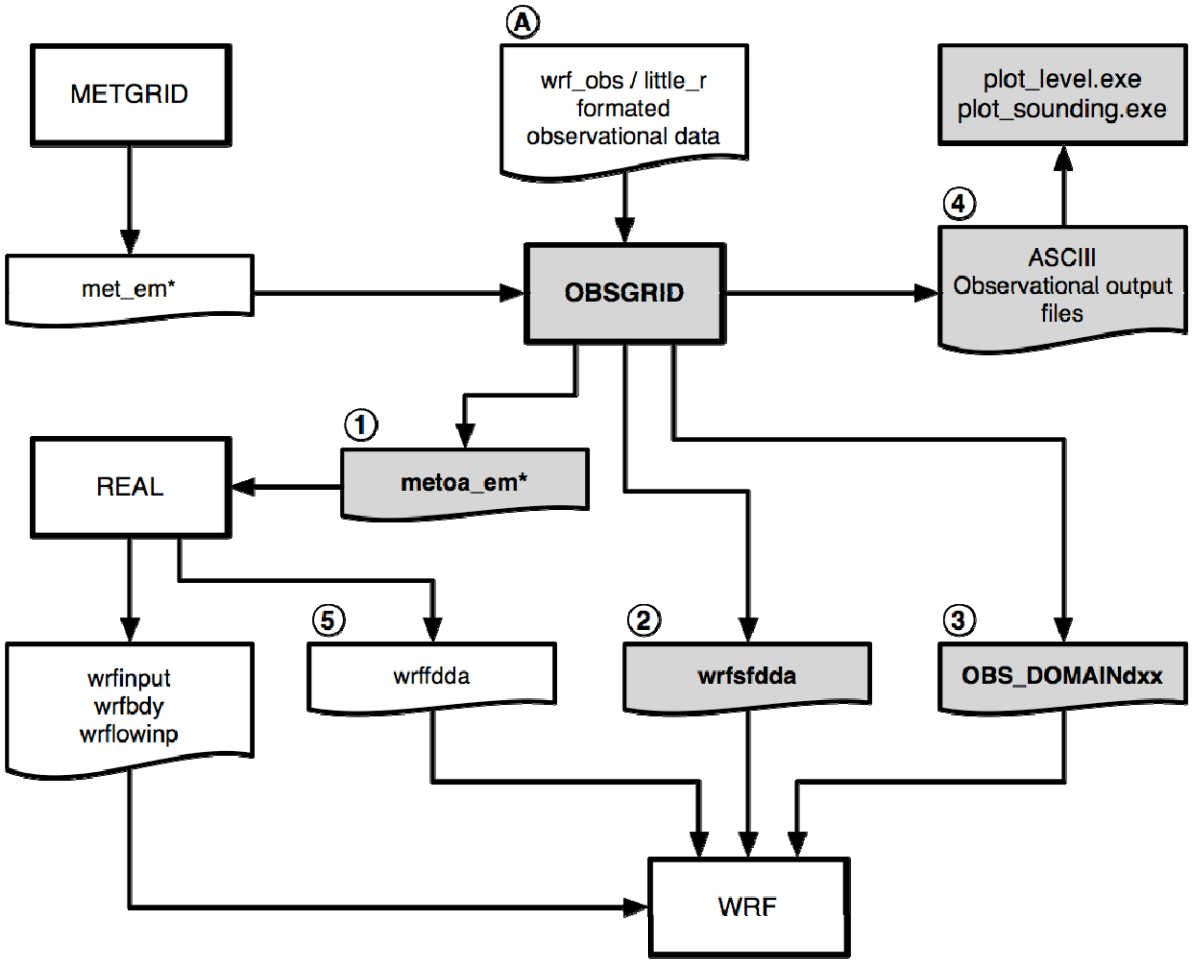
OBSGRID capabilities include:

- Choice of Cressman-style or Multiquadric objective analysis.

- Various tests to screen the data for suspect observations.
- Procedures to input bogus data.
- Expanded Grid: OBSGRID has the capability to cut the input model domain down on output. This feature allows you to incorporate data from outside your intended grid to improve analyses near the boundaries. To use this feature, a user must create a larger domain than the final intended domain when running WPS.

Program Flow

OBSGRID is run directly after metgrid.exe, and uses the *met_em** output files from metgrid.exe as input. OBSGRID also requires additional observations (**A**) as input. The format of these observational files is described in the Observations Format section of this chapter.



Output from the objective analysis programs can be used to:

- Provide fields for Initial and Boundary conditions (1). Note that the files *metoa_em** are formatted identical to the *met_em** files from metgrid.exe. The only difference is that the fields in these files now incorporate observational information.
- Provide surface fields for surface-analysis-nudging *FDDA (2)*. Note, when using the *wrfsfdda* file as input to WRF, it is also recommended to use the 3-D fdda file *(wrffdda (5) – which is an optional output created when running real.exe)* as input to WRF.
- Provide data for observational nudging (3). Note: since version 3.1.1 of OBSGRID this file can be read directly by the observational nudging code and no longer needs to pass through an additional perl script.
- Provide ASCII output (4). These files provide information regarding the observations used and the quality control flags assigned. The information in these files can also be plotted with the provided plotting utilities.

Source of Observations

OBSGRID reads observations provided by the user in formatted ASCII text files. This allows users to adapt their own data to use as input to the OBSGRID program. This format (*wrf_obs / little_r format*) is the same format used in the MM5 objective analysis program LITTLE_R (*hence the name*).

Programs are available to convert NMC ON29 formatted files (*see below*) into the wrf_obs / little_r format. Users are responsible for converting other observations they may want to provide to OBSGRID into this format. A user-contributed (*i.e., unsupported*) program is available in the utils/ directory for converting observations files from the GTS to wrf_obs / little_r format.

NCEP operational global surface and upper-air observations subsets as archived by the Data Support Section (DSS) at *NCAR*.

- Upper-air data: *RAOBS* (*ADPUPA*), in *NMC ON29* format.
- Surface data: *NMC* Surface *ADP* data, in *NMC ON29* format.

NMC Office Note 29 can be found in many places on the World Wide Web, including: http://www.emc.ncep.noaa.gov/mmb/data_processing/on29.htm

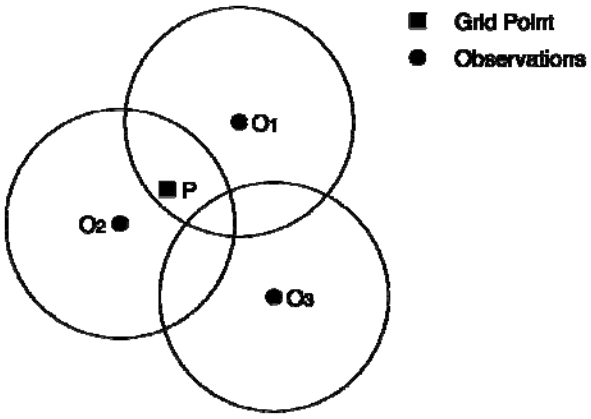
Objective Analysis techniques in OBSGRID

Cressman Scheme

Three of the four objective analysis techniques used in OBSGRID are based on the Cressman scheme; in which several successive scans nudge a first-guess field toward the neighboring observed values.

The standard Cressman scheme assigns to each observation a circular radius of influence R. The first-guess field at each grid point P is adjusted by taking into account all the observations that influence P.

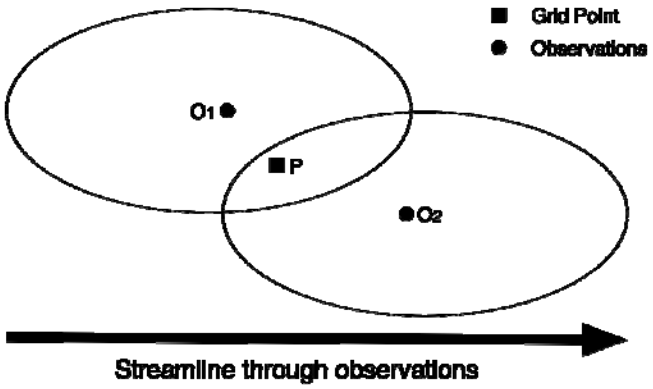
The differences between the first-guess field and the observations are calculated, and a distance-weighted average of these difference values is added to the value of the first-guess at P. Once all grid points have been adjusted, the adjusted field is used as the first guess for another adjustment cycle. Subsequent passes each use a smaller radius of influence.



Observations O_1 and O_2 influence grid point P, O_3 does not.

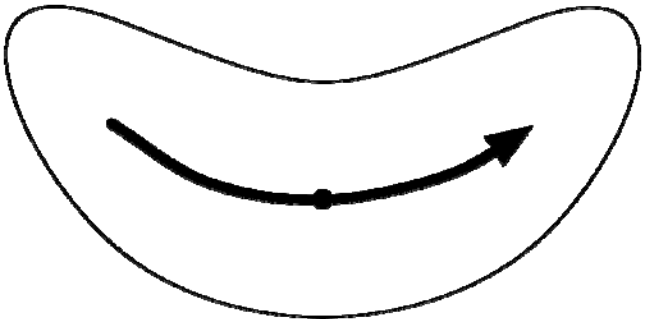
Ellipse Scheme

In analyses of wind and relative humidity (fields strongly deformed by the wind) at pressure levels, the circles from the standard Cressman scheme are elongated into ellipses oriented along the flow. The stronger the wind, the greater the eccentricity of the ellipses. This scheme reduces to the circular Cressman scheme under low-wind conditions.



Banana Scheme

In analyses of wind and relative humidity at pressure levels, the circles from the standard Cressman scheme are elongated in the direction of the flow and curved along the streamlines. The result is a banana shape. This scheme reduces to the Ellipse scheme under straight-flow conditions, and the standard Cressman scheme under low-wind conditions.



Multiquadric scheme

The Multiquadric scheme uses hyperboloid radial basis functions to perform the objective analysis. Details of the multiquadric technique may be found in Nuss and Titley, 1994: "Use of multiquadric interpolation for meteorological objective analysis." *Mon . Wea . Rev .*, 122, 1611-1631. Use this scheme with caution, as it can produce some odd results in areas where only a few observations are available.

Quality Control for Observations

A critical component of OBSGRID is the screening for bad observations. Many of these QC checks are optional in OBSGRID.

Quality Control on Individual Reports

- Gross Error Checks (sane values, pressure decreases with height, etc.)
- Remove spikes from temperature and wind profiles.
- Adjust temperature profiles to remove superadiabatic layers.
- No comparisons to other reports or to the first-guess field.

The ERRMAX test

The ERRMAX quality-control check is optional, but highly recommended.

- Limited user control over data removal. The user may set thresholds, which vary the tolerance of the error check.
- Observations are compared to the first-guess field.
- If the difference value (obs - first-guess) exceeds a certain threshold, the observation is discarded.
- Threshold varies depending on the field, level, and time of day.
- Works well with a good first-guess field.

The Buddy test

The Buddy check is optional, but highly recommended.

- Limited user control over data removal. The user may set weighting factors, which vary the tolerance of the error check.
- Observations are compared to both the first guess and neighboring observations.
- If the difference value of an observation (obs - first-guess) varies significantly from the distance-weighted average of the difference values of neighboring observations, the observation is discarded.
- Works well in regions with good data density.

Additional Observations

Input of additional observations, or modification of existing (*and erroneous*) observations, can be a useful tool at the objective analysis stage.

In OBSGRID, additional observations are provided to the program the same way (*in the same wrf_obs / little_r format*) as standard observations. Additional observations must be in the same file as the rest of the observations. Existing (*erroneous*) observations can be modified easily, as the observations input format is ASCII text. Identifying an observation report as "bogus" simply means that it is assumed to be good data -- no quality control is performed for that report.

Surface FDDA option

The surface FDDA option creates additional analysis files for the surface only, usually with a smaller time interval between analyses (*i.e., more frequently*) than the full upper-air analyses. The purpose of these surface analysis files is for later use in WRF with the surface analysis nudging option.

The LAGTEM option controls how the first-guess field is created for surface analysis files. Typically, the surface and upper-air first-guess (*analysis times*) is available at twelve-hour or six-hour intervals, while the surface analysis interval may be 3 hours (*10800 seconds*). So at analysis times, the available surface first-guess is used. If LAGTEM is set to .**FALSE**., the surface first-guess at other times will be temporally interpolated from the first-guess at the analysis times. If

LAGTEM is set to .**TRUE**., the surface first guess at other times is the objective analysis from the previous time.

Objective Analysis on Model Nests

OBSGRID have the capability to perform the objective analysis on a nest. This is done manually with a separate OBSGRID process, performed on met_em_d0x files for the particular nest. Often, however, such a step is unnecessary; it complicates matters for the user and may introduce errors into the forecast. At other times, extra information available to the user, or extra detail that objective analysis may provide on a nest, makes objective analysis on a nest a good option.

The main reason to do objective analysis on a nest is if you have observations available with horizontal resolution somewhat greater than the resolution of your coarse domain. There may also be circumstances in which the representation of terrain on a nest allows for better use of surface observations (*i.e., the model terrain better matches the real terrain elevation of the observation*).

The main problem introduced by doing objective analysis on a nest is inconsistency in initial conditions between the coarse domain and the nest. Observations that fall just outside a nest will be used in the analysis of the coarse domain, but discarded in the analysis of the nest. With different observations used right at a nest boundary, one can get very different analyses.

How to run OBSGRID

Get the source code

The source code can be downloaded from: http://www.mmm.ucar.edu/wrf/download/get_source.html. Once the tar file is gunzipped (gunzip OBSGRID.TAR.gz), and untared (untar OBSGRID.TAR), and it will create an OBSGRID/ directory.

```
cd OBSGRID
```

Generate the executable

The only library that is required to build the WRF model is NetCDF. The user can find the source code, precompiled binaries, and documentation at the UNIDATA home page (http://www.unidata.ucar.edu/software/netcdf/).

To successfully compile the utilities `plot_level.exe` and `plot_sounding.exe`, NCAR Graphics needs to be installed on your system. These routines are not necessary to run OBSGRID, but are useful for displaying observations.

To configure, type:

```
./configure
```

Choose one of the configure options, then compile.

```
./compile
```

If successful, this will create the executable `obsgrid.exe`. Executables `plot_level.exe` and `plot_sounding.exe`, will be created if NCAR Graphics is installed.

Prepare the observations files

Preparing observational files is a user responsibility.

A program is available for users with access to NCAR's computers to download archived observations and reformat them into the wrf_obs/little_r format.

A program is also available for reformatting observations from the GTS stream (*unsupported*).

The code expects to find one observational input file per analysis time.

Edit the namelist for your specific case

The most critical information you'll be changing most often is the start date, end date, and file names.

Pay particularly careful attention to the file name settings. Mistakes in observations file names can go unnoticed because OBSGRID will happily process the wrong files, and if there are no data in the (*wrongly-specified*) file for a particular time, OBSGRID will happily provide you with an analysis of no observations.

Run the program

Run the program by invoking the command:

```
./obsgrid.exe >& obsgrid.out
```

Check the `obsgrid.out` file for information and runtime errors.

Check your output

Examine the `obsgrid.out` file for error messages or warning messages. The program should have created the files called `metoa_em*.` Additional output files containing information about observations found and used and discarded will probably be created, as well.

Important things to check include the number of observations found for your objective analysis, and the number of observations used at various levels. This can alert you to possible problems in specifying observations files or time intervals. This information is included in the printout file.

You may also want to experiment with a couple of simple plot utility programs, discussed below.

There are a number of additional output files, which you might find useful. These are discussed below.

Output Files

The OBSGRID program generates some ASCII text files to detail the actions taken on observations through a time cycle of the program. In support of users wishing to plot the observations used for each variable (at each level, at each time), a file is created with this information. Primarily, the ASCII text files are for consumption by the developers for diagnostic purposes. The main output of the OBSGRID program is the gridded, pressure-level data set to be passed to the real.exe program (files `metoa_em`*).

In each of the files listed below, the text ".d*n*.YYYY-MM-DD_HH:mm:ss.tttt" allows each time period that is processed by OBSGRID to output a separate file. The only unusual information in the date string is the final four letters "tttt" which is the decimal time to ten thousandths of a second. These files will be dependant on the domain being processed.

metoa_em*

The final analysis files at surface and pressure levels. Generating this file is the primary goal of running OBSGRID.

These files can now be used in place of the *met_em** files from WPS to generate initial and boundary conditions for WRF. To use these files when running real.exe you can do one of two things:

1. Rename or link the *metoa_em** files back to *met_em**. This way real.exe will read the files automatically.
2. Use the *auxinput1_inname* namelist option in WRF's namelist.input file to overwrite the default filename real.exe uses. To do this, add the following to the *&time_control* section of the WRF namelist.input file before running real.exe *(use the exact syntax as below – do not substitute the <domain> and <date> for actual numbers)*:

```
auxinput1_inname = "metoa_em.d<domain>.<date>"
```

wrfsfdda_d*n*

Use of the surface FDDA option in OBSGRID creates a file called `wrfsfdda_d`*n* This file contains the surface analyses at INTF4D intervals, analyses of T, TH, U, V, RH, QV, PSFC, PMSL, and a count of observations within 250 km of each grid point.

Due to the input requirements of the WRF model, data at the current time (_OLD) and data for the next time (_NEW) are supplied at each time interval. *Due to this requirement, users must take care to specify the same interval in the WRF fdda section for surface nudging as the interval used in OBSGRID to create the wrfsfdda_dn file*.

OBS_DOMAIN*dxx*

These files can be used in WRF for observational nudging. The format of this file is slightly different from the standard *wrf_obs / little_r* format. *See Chapter 5 of this User's Guide for details on observational nudging.*

The "*d*" in the file name represents the domain number. The "*xx*" is just a sequential number.

These files contain a list of all of the observations available for use by the OBSGRID program.

- The observations have been sorted and the duplicates have been removed.
- Observations outside of the analysis region have been removed.
- Observations with no information have been removed.
- All reports for each separate location *(different levels but at the same time)* have been combined to form a single report.
- Data which has had the "discard" flag internally set *(data which will not be sent to the quality control or objective analysis portions of the code)* are not listed in this output.
- The data has gone through an expensive test to determine if the report is within the analysis region, and the data have been given various quality control flags. Unless a blatant error in the data is detected *(such as a negative sea-level pressure),* the observation data are not typically modified, but only assigned quality control flags.
- Data with qc flags higher than a specified values *(user controlled via the namelist),* will be set to missing data.

qc_obs_raw.d*n*.YYYY-MM-DD_HH:mm:ss.tttt

This file contains a listing of all of the observations available for use by the OBSGRID program.

- The observations have been sorted and the duplicates have been removed.
- Observations outside of the analysis region have been removed.
- Observations with no information have been removed.

- All reports for each separate location *(different levels but at the same time)* have been combined to form a single report.
- Data which has had the "discard" flag internally set *(data which will not be sent to the quality control or objective analysis portions of the code)* are not listed in this output.
- The data has gone through an expensive test to determine if the report is within the analysis region, and the data have been given various quality control flags. Unless a blatant error in the data is detected *(such as a negative sea-level pressure),* the observation data are not typically modified, but only assigned quality control flags.
- *This data can be used as input to the plotting utility plot_sounding.exe*

qc_obs_used.d*n*.YYYY-MM-DD_HH:mm:ss.tttt

This file contains exactly the same data as in the OBS_DOMAINdxx file, but in this case the format is standard *wrf_obs/little_r* data format.

plotobs_out.d*n*.YYYY-MM-DD_HH:mm:ss.tttt

This file lists data by variable and by level, where each observation that has gone into the objective analysis is grouped with all of the associated observations for plotting or some other diagnostic purpose. The first line of this file is the necessary FORTRAN format required to input the data. There are titles over the data columns to aid in the information identification. Below are a few lines from a typical file. *This data can be used as input to the plotting utility plot_level.exe*

```
( 3x,a8,3x,i6,3x,i5,3x,a8,3x,2(g13.6,3x),2(f7.2,3x),i7 )
Number of Observations 00001214
Variable Press  Obs    Station Obs        Obs-1st   X         Y         QC
Name     Level  Number ID      Value      Guess     Location  Location  Value
U        1001   1      CYYT    6.39806    4.67690   161.51    122.96    0
U        1001   2      CWRA    2.04794    0.891641  162.04    120.03    0
U        1001   3      CWVA    1.30433   -1.80660   159.54    125.52    0
U        1001   4      CWAR    1.20569    1.07567   159.53    121.07    0
U        1001   5      CYQX    0.470500  -2.10306   156.58    125.17    0
U        1001   6      CWDO    0.789376  -3.03728   155.34    127.02    0
U        1001   7      CWDS    0.846182   2.14755   157.37    118.95    0
```

Plot Utilities

The OBSGRID package provides two utility programs for plotting observations. These programs are called `plot_soundings.exe` and `plot_levels.exe`. These optional programs use NCAR Graphics, and are built. Both programs get additional input options from the `namelist.oa` file.

plot_soundings.exe

Program `plot_soundings.exe` plots soundings. This program generates soundings from the "qc_obs_raw.d*n*.YYYY-MM-DD_HH:mm:ss.tttt" and "qc_obs_used.d*n*.YYYY-MM-DD_HH:mm:ss.tttt" data files. Only data that are on the requested analysis levels are processed.

The program uses information from `&record1, &record2` and `&plot_souding` in the `namelist.oa` file to generate the required output.

The program create output file(s): `sounding_<`*`file_type`*`>_<`*`date`*`>.cgm`

plot_level.exe

Program `plot_level.exe` creates station plots for each analysis level. These plots contain both observations that have passed all QC tests and observations that have failed the QC tests. Observations that have failed the QC tests are plotted in various colors according to which test failed.

The program uses information from `&record1` and `&record2` in the `namelist.oa` file to generate plots from the observations in the file "plotobs_out.dn.YYYY-MM-DD_HH:mm:ss.tttt".

The program creates the file(s): `levels_<`*`date`*`>.cgm` or `levels_sfc_fdda_<`*`date`*`>.cgm,` depending on which file type is plotted.

Observations Format

To make the best use of the OBSGRID program, it is important for users to understand the *wrf_obs/little_r* Observations Format.

Observations are conceptually organized in terms of reports. A report consists of a single observation or set of observations associated with a single latitude/longitude coordinate.

Examples

- a surface station report including observations of temperature, pressure, humidity, and winds.
- an upper-air station's sounding report with temperature, humidity, and wind observations at many height or pressure levels.
- an aircraft report of temperature at a specific lat/lon/height.
- a satellite-derived wind observation at a specific lat/lon/height.

Each report in the *wrf_obs/little_r* Observations Format consists of at least four records:

- A *report header record*
- one or more *data records*
- an *end data record*
- an *end report record* .

The *report header record* is a 600-character long record (*much of which is unused and needs only dummy values*) that contains certain information about the station and the report as a whole: location, station id, station type, station elevation, etc. The report header record is described fully in the following table. Shaded items in the table are unused:

Report header format

Variable	Fortran I/O Format	Description
latitude	F20.5	station latitude (north positive)
longitude	F20.5	station longitude (east positive)
id	A40	ID of station
name	A40	Name of station
platform	A40	Description of the measurement device
source	A40	GTS, NCAR/ADP, BOGUS, etc.
elevation	F20.5	station elevation (m)
num_vld_fld	I10	Number of valid fields in the report
num_error	I10	Number of errors encountered during the decoding of this observation
num_warning	I10	Number of warnings encountered during decoding of this observation.
seq_num	I10	Sequence number of this observation
num_dups	I10	Number of duplicates found for this observation
is_sound	L10	T/F Multiple levels or a single level
bogus	L10	T/F bogus report or normal one
discard	L10	T/F Duplicate and discarded (or merged) report.
sut	I10	Seconds since 0000 UTC 1 January 1970
julian	I10	Day of the year
date_char	A20	YYYYMMDDHHmmss
slp, qc	F13.5, I7	Sea-level pressure (Pa) and a QC flag

ref_pres, qc	F13.5, I7	Reference pressure level (for thickness) (Pa) and a QC flag
ground_t, qc	F13.5, I7	Ground Temperature (T) and QC flag
sst, qc	F13.5, I7	Sea-Surface Temperature (K) and QC
psfc, qc	F13.5, I7	Surface pressure (Pa) and QC
precip, qc	F13.5, I7	Precipitation Accumulation and QC
t_max, qc	F13.5, I7	Daily maximum T (K) and QC
t_min, qc	F13.5, I7	Daily minimum T (K) and QC
t_min_night, qc	F13.5, I7	Overnight minimum T (K) and QC
p_tend03, qc	F13.5, I7	3-hour pressure change (Pa) and QC
p_tend24, qc	F13.5, I7	24-hour pressure change (Pa) and QC
cloud_cvr, qc	F13.5, I7	Total cloud cover (oktas) and QC
ceiling, qc	F13.5, I7	Height (m) of cloud base and Q

Following the report header record are the *data records*. These data records contain the observations of pressure, height, temperature, dewpoint, wind speed, and wind direction. There are a number of other fields in the data record that are not used on input. Each data record contains data for a single level of the report. For report types that have multiple levels (*e.g., upper-air station sounding reports*), each pressure or height level has its own data record. For report types with a single level (*such as surface station reports or a satellite wind observation*), the report will have a single data record. The data record contents and format are summarized in the following table

Format of data records		
Variable	**Fortran I/O Format**	**Description**
pressure, qc	F13.5, I7	Pressure (Pa) of observation, and QC
height, qc	F13.5, I7	Height (m MSL) of observation, and QC
temperature, qc	F13.5, I7	Temperature (K) and QC
dew_point, qc	F13.5, I7	Dewpoint (K) and QC
speed, qc	F13.5, I7	Wind speed (m s ***-1***) and QC
direction, qc	F13.5, I7	Wind direction (degrees) and QC
u, qc	F13.5, I7	u component of wind (m s ***-1***), and QC
v, qc	F13.5, I7	v component of wind (m s ***-1***), and QC
rh, qc	F13.5, I7	Relative Humidity (%) and QC
thickness, qc	F13.5, I7	Thickness (m), and Q

The *end data record* is simply a data record with pressure and height fields both set to -777777.

After all the data records and the end data record, an *end report record* must appear. The end report record is simply three integers, which really aren't all that important.

Format of end_report records

Variable	Fortran I/O Format	Description
num_vld_fld	I7	Number of valid fields in the report
num_error	I7	Number of errors encountered during the decoding of the report
num_warning	I7	Number of warnings encountered during the decoding the report

QCFlags

In the observations files, most of the meteorological data fields also have space for an additional integer quality-control flag. The quality control values are of the form 2n, where n takes on positive integer values. This allows the various quality control flags to be additive yet permits the decomposition of the total sum into constituent components. Following are the current quality control flags that are applied to observations.

```
pressure interpolated from first-guess height      = 2 **  1 =      2
temperature and dew point both = 0                 = 2 **  4 =     16
wind speed and direction both = 0                  = 2 **  5 =     32
wind speed negative                                = 2 **  6 =     64
wind direction < 0 or > 360                        = 2 **  7 =    128
level vertically interpolated                      = 2 **  8 =    256
value vertically extrapolated from single level    = 2 **  9 =    512
sign of temperature reversed                       = 2 ** 10 =   1024
superadiabatic level detected                      = 2 ** 11 =   2048
vertical spike in wind speed or direction          = 2 ** 12 =   4096
convective adjustment applied to temperature field = 2 ** 13 =   8192
no neighboring observations for buddy check        = 2 ** 14 =  16384
-------------------------------------------------------------------------
fails error maximum test                           = 2 ** 15 =  32768
fails buddy test                                   = 2 ** 16 =  65536
observation outside of domain detected by QC       = 2 ** 17 = 131072
```

OBSGRID Namelist

The OBSGRID namelist file is called "namelist.oa", and must be in the directory from which OBSGRID is run. The namelist consists of nine namelist records, named "record1" through "record9", each having a loosely related area of content. Each namelist record, which extends

over several lines in the namelist.oa file, begins with "&record<#>" (where <#> is the namelist record number) and ends with a slash "/".

The namelist record &plot_sounding is only used by the corresponding utility.

Namelist record1

The data in namelist record1 define the analysis times to process:

Namelist Variable	Value	Description
start_year	2000	4-digit year of the starting time to process
start_month	01	2-digit month of the starting time to process
start_day	24	2-digit day of the starting time to process
start_hour	12	2-digit hour of the starting time to process
end_year	2000	4-digit year of the ending time to process
end_month	01	2-digit month of the ending time to process
end_day	25	2-digit day of the ending time to process
end_hour	12	2-digit hour of the ending time to process
interval	21600	Time interval (s) between consecutive times to process

Namelist record2

The data in record2 define the model grid and names of the input files:

Namelist Variable	Value	Description
domain_id	1	ID of domain to process
obs_filename	CHARACTER	Root file name (*may include directory information*) of the observational files. All input files must have the format obs_filename:<YYYY-MM-DD_HH>. One file required for each time period. If a wrfsfdda is being created, then similar input data files are required for each surface fdda time.

remove_data_above_qc_flag	200000	Data with qc flags higher than this will not be output to the OBS_DOMAIN*dxx* files. Default is to output all data. Use 32768 to remove data that failed the buddy and error max tests. This does not affect the data used in the OA process.
remove_unverified_data	.FALSE.	When input data is not on an analysis level, the data cannot be QC-ed. This data is never used in the OA process, but may make its way into the ASCII output files. By setting this parameter to .TRUE. these observations will be removed from the *OBS_DOMAINdxx* files.
trim_domain	.FALSE.	Set to .TRUE. if this domain must be cut down on output
trim_value	5	Value by which the domain will be cut down in each direction

The *met_em** files which are being processed must be available in the OBSGRID/ directory.

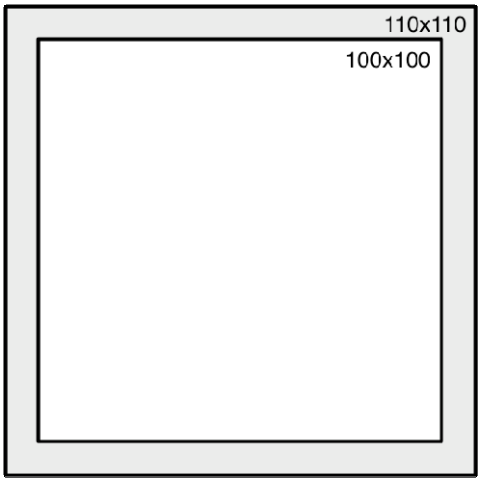
The obs_filename and interval settings can get confusing, and deserve some additional explanation. Use of the *obs_filename* files is related to the times and time interval set in namelist `&record1`, and to the F4D options set in namelist `&record8`. The *obs_filename* files are used for the analyses of the full 3D dataset, both at upper-air and the surface. They are also used when F4D=.TRUE., that is, if surface analyses are being created for surface FDDA nudging. The *obs_filename* files should contain all observations, upper-air and surface, to be used for a particular analysis at a particular time.

Ideally there should be an obs_filename for each time period for which an objective analysis is desired. Time periods are processed sequentially from the starting date to the ending date by the time interval, all specified in namelist `&record1`. All observational files must have a date associated. If a file is not found, the code will process as if this file contains zero observations, and then continue to the next time period.

If the F4D option is selected, the *obs_filename* files are similarly processed for surface analyses, this time with the time interval as specified by INTF4D.

If a users wishes to include observations from outside the interested model domain, geogrid.exe (WPS) needs to be run for a slightly large domain that the domain of interest. Setting `trim_domain` to .TRUE. will cut all 4 directions of the input domain down by the number of grid points set in `trim_value`.

In the example below, the domain of interest is the inner white domain with a total of 100x100 grid points. geogrid.exe have be run for the outer domain (110x110 grid points). By setting `trim_value` to 5, the output domain will be trimmed by 5 grid points in each direction, resulting in the white 100x100 grid point domain.



Namelist record3

The data in the record3 concern space allocated within the program for observations. These are values that should not frequently need to be modified:

Namelist Variable	Value	Description
max_number_of_obs	10000	Anticipated maximum number of reports per time period
fatal_if_exceed_max_obs	.TRUE.	T/F flag allows the user to decide the severity of not having enough space to store all of the available observation

Namelist record4

The data in record4 set the quality control options. There are four specific tests that may be activated by the user: An error max test; a buddy test; removal of spike, and; the removal of super-adiabatic lapse rates. For some of these tests a user have control over the tolerances as well.

Namelist Variable	Value	Description
Error Max Test: For this test there is a threshold for each variable. These values are scaled for time of day, surface characteristics and vertical level.		
qc_test_error_max	.TRUE.	Check the difference between the first-guess and the observation
max_error_t	10	Maximum allowable temperature difference (K)
max_error_uv	13	Maximum allowable horizontal wind component difference (m/s)
max_error_z	*8*	*Not used*
max_error_rh	50	Maximum allowable relative humidity difference (%)
max_error_p	600	Maximum allowable sea-level pressure difference (Pa
Buddy Check Test: For this test there is a threshold for each variable. These values are similar to standard deviations.		
qc_test_buddy	.TRUE.	Check the difference between a single observation and neighboring observations
max_buddy_t	8	Maximum allowable temperature difference (K)
max_buddy_uv	8	Maximum allowable horizontal wind component difference (m/s)
max_buddy_z	*8*	*Not used*
max_buddy_rh	40	Maximum allowable relative humidity difference (%)
max_buddy_p	800	Maximum allowable sea-level pressure difference (Pa)
buddy_weight	1.0	Value by which the buddy thresholds are scale
Spike removal		
qc_test_vert_consistency	.FALSE.	Check for vertical spikes in temperature, dew point, wind speed and wind direction
Removal of super-adiabatic lapse rates		
qc_test_convective_adj	.FALSE.	Remove any super-adiabatic lapse rate in a sounding by conservation of dry static energy

For satellite and aircraft observations, data are often horizontally spaced with only a single vertical level. The following two entries describe how far the user assumes that the data are valid in pressure space.		
max_p_extend_t	1300	Pressure difference (Pa) through which a single temperature report may be extended
max_p_extend_w	1300	Pressure difference (Pa) through which a single wind report may be extended

Namelist record5

The data in record5 control the enormous amount of printout that may be produced by the OBSGRID program. These values are all logical flags, where TRUE will generate output and FALSE will turn off output.

```
print_obs_files ; print_found_obs ; print_header ;
print_analysis ;print_qc_vert ; print_qc_dry ;
print_error_max ; print_buddy ;print_oa
```

Namelist record7

The data in record7 concerns the use of the first-guess fields, and surface FDDA analysis options. Always use the first guess.

Namelist Variable	Value	Description
use_first_guess	.TRUE.	Always use first guess (use_first_guess=.TRUE.)
f4d	.TRUE.	Turns on (.TRUE.) or off (.FALSE.) the creation of surface analysis files.
intf4d	10800	Time interval in seconds between surface analysis times
lagtem	.FALSE.	Use the previous time-period's final surface analysis for this time-period's first guess (lagtem=.TRUE.); or Use a temporal interpolation between upper-air times as the first guess for this surface analysis (lagtem = .FALSE.)

Namelist record8

The data in record8 concern the smoothing of the data after the objective analysis. The differences (*observation minus first-guess*) of the analyzed fields are smoothed, not the full fields.

Namelist Variable	Value	Description
smooth_type	1	1 = five point stencil of 1-2-1 smoothing; 2 = smoother-desmoother
smooth_sfc_wind	0	Number of smoothing passes for surface winds
smooth_sfc_temp	0	Number of smoothing passes for surface temperature
smooth_sfc_rh	0	Number of smoothing passes for surface relative humidity
smooth_sfc_slp	0	Number of smoothing passes for sea-level pressure
smooth_upper_wind	0	Number of smoothing passes for upper-air winds
smooth_upper_temp	0	Number of smoothing passes for upper-air temperature
smooth_upper_rh	0	Number of smoothing passes for upper-air relative humidity

Namelist record9

The data in record9 concern the objective analysis options. There is no user control to select the various Cressman extensions for the radius of influence (*circular, elliptical or banana*). If the Cressman option is selected, ellipse or banana extensions will be applied as the wind conditions warrant.

Namelist Variable	Value	Description
oa_type	"Cressman"	"MQD" for multiquadric; "Cressman" for the Cressman-type scheme, this string is case sensitive
oa_3D_type	"Cressman"	Set upper-air scheme to "Cressman", regardless of the scheme used at the surface
oa_3D_option	0	How to switch between "MQD" and "Cressman" if not enough observations are available to perform "MQD"

mqd_minimum_num_obs	30	Minimum number of observations for MQD
mqd_maximum_num_obs	1000	Maximum number of observations for MQD
radius_influence	5,4,3,2	Radius of influence in grid units for Cressman scheme
oa_min_switch	.TRUE.	T = switch to Cressman if too few observations for MQD; F = no analysis if too few observations
oa_max_switch	.TRUE.	T = switch to Cressman if too many observations for MQD; F = no analysis if too many observation

When oa_type is set to *Cressman*, then the *Cressman* scheme will be performed on all data.

When oa_type is set to *MQD*, there is a wide variety of options available controlling when the code will revert back to the *Cressman* scheme.

- oa_max_switch ; mqd_maximum_num_obs
  The code will revert back to *Cressman* if the switch is set to true and the maximum number of observations is exceeded.
  This is reduce the time the code run and not for physical reasons.
  Recommended to left switch set to true and just set the maximum number large.

- oa_min_switch ; mqd_minimum_num_obs
  The code will revert back to *Cressman* if the switch is set to true and there are too few observations. How and when the code reverts back to Cressman under these conditions, are controlled by the oa_3D_option parameter.
  Recommended to left switch set to true and start with the default minimum settings.

- oa_3D_type="Cressman"
  All upper-air levels will use *Cressman* scheme, regardless of other settings.

  Surface will use *MQD* as long as there are enough observations to do so (mqd_maximum_num_obs ; mqd_minimum_num_obs), else it will also revert to the *Cressman* scheme.
  Note, that if some time periods have enough observations and others does not, the code will only revert to *Cressman* for the times without sufficient observations.

- oa_3D_option
  There are three options (0,1,2). For all these options the surface will use *MQD* as long as there are enough observations to do so (mqd_maximum_num_obs ; mqd_minimum_num_obs), else it will also revert to the *Cressman* scheme.
  Note, that if some time periods have enough observations and others does not, the code

will only revert to *Cressman* for the times without sufficient observations.

The upper-air will react as follows:
0 (default): MQD is performed in the upper-air as long as there are enough observations to do so (`mqd_maximum_num_obs ; mqd_minimum_num_obs`). As soon as this is on longer the case, the code will STOP, with suggestions as to which parameters to set to run the code correctly.

1: The code will first check to see if, for a given time, all levels and variables in the upper-air have sufficient observations for the *MQD* scheme. If not, the code will revert to Cressman for that time period. Note, that if some time periods have enough observations and others does not, the code will only revert to *Cressman* for the times without sufficient observations.

2: The code will check per time, level and variable if sufficient observations are available for the *MQD* scheme. If not, the code will revert to the *Cressman* scheme for that particular time, level and variable. Note, as this can result in uncontrolled switching between *MQD* and *Cressman*, this option is not recommended.

`radius_influence`
There are three ways to set the radius of influence (RIN) for the *Cressman* scheme:

- Manually: Set the RIN and number of scans directly. E.g., 5,4,3,2, will result in 4 scans. The first will use 5 grid points for the RIN and the last 2 points.
- Automatically 1: Set RIN to 0 and the code will calculate the RIN based on the domain size and an estimated observation density of 325km. By default there will be 4 scans.
- Automatically 2: Set RIN to a negative number and the code will calculate the RIN based on the domain size and an estimated observation density of 325km. The number of scans is controlled by the value of the set number. E.g, -5 will result in 5 scans.

Namelist plot_sounding

Only used for the utility plot_sounding.exe

Namelist Variable	Value	Description
file_type	"raw"	File to read to produce the plots. Options are "raw" or "used"
read_metoa	.TRUE.	If set to .TRUE., the model domain information in the metoa_em files will be used to add location information on the plot.

Chapter 8: WRF Software

Table of Contents

Introduction

WRF Build Mechanism

The WRF build mechanism provides a uniform apparatus for configuring and compiling the WRF model, WRF-Var system and the WRF pre-processors over a range of platforms with a variety of options. This section describes the components and functioning of the build mechanism. For information on building the WRF code, see the chapter on Software Installation.

Required software:

The WRF build relies on Perl version 5 or later and a number of UNIX utilities: csh and Bourne shell, make, M4, sed, awk, and the uname command. A C compiler is needed to compile programs and libraries in the tools and external directories. The WRF code itself is standard Fortran (commonly referred to as Fortran90). For distributed-memory processing, MPI and related tools and libraries should be installed.

Build Mechanism Components:

Directory structure: The directory structure of WRF consists of the top-level directory plus directories containing files related to the WRF software framework (**`frame`**), the WRF model (**`dyn_em`**, **`phys`**, **`chem`**, **`share`**), WRF-Var (**`da`**), configuration files (**`arch`**, **`Registry`**), helper and utility programs (**`tools`**), and packages that are distributed with the WRF code (**`external`**).

Scripts: The top-level directory contains three user-executable scripts: **`configure`**, **`compile`**, and **`clean`**. The configure script relies on the Perl script in **`arch/Config_new.pl`**.

Programs: A significant number of WRF lines of code are automatically generated at compile time. The program that does this is **`tools/registry`** and it is distributed as part of the source code with the WRF model.

Makefiles: The main **`Makefile`** (input to the UNIX make utility) is in the top-level directory. There are also makefiles in most of the subdirectories that come with WRF. Make is called recursively over the directory structure. Make is not directly invoked by the user to compile WRF; the **`compile`** script is provided for this purpose.

Configuration files: The **`configure.wrf`** contains compiler, linker, and other build settings, as well as rules and macro definitions used by the make utility. The **`configure.wrf`** file is included by the Makefiles in most of the WRF source distribution (Makefiles in tools and external directories do not include configure.wrf). The **`configure.wrf`** file in the top-level directory is generated each time the configure script is invoked. It is also deleted by clean -a. Thus, **`configure.wrf`** is the place to make temporary changes, such as optimization levels and compiling with debugging, but permanent changes should be made in the file **`arch/configure_new.defaults`**. The **`configure.wrf`** file is composed of three files: **`arch/preamble_new`** **`arch/postamble_new`** and **`arch_configure_new.defaults`**.

The **`arch/configure_new.defaults`** file contains lists of compiler options for all the supported platforms and configurations. Changes made to this file will be permanent. This file is used by the **`configure`** script to generate a temporary **`configure.wrf`** file in the top-level directory. The **`arch`** directory also contains the files **`preamble_new`** and **`postamble_new`**, which constitute the generic parts (non-architecture specific) of the **`configure.wrf`** file that is generated by the **`configure`** script.

The **`Registry`** directory contains files that control many compile-time aspects of the WRF code. The files are named **`Registry.`*`core`*** (where ***`core`*** is for example ***`EM`***). The **`configure`** script copies one of these to **`Registry/Registry`**, which is the file that **`tools/registry`** will use as input. The choice of ***`core`*** depends on settings to the **`configure`** script. Changes to **`Registry/Registry`** will be lost; permanent changes should be made to **`Registry.`*`core`***. For the WRF ARW model, the file is typically **`Registry.EM`**.

Environment variables: Certain aspects of the configuration and build are controlled by environment variables: the non-standard locations of NetCDF libraries or the Perl command, which dynamic core to compile, machine-specific features, and optional build libraries (such as Grib Edition 2, HDF, and parallel netCDF).

In addition to WRF-related environment settings, there may also be settings specific to particular compilers or libraries. For example, local installations may require setting a variable like **MPICH_F90** to make sure the correct instance of the Fortran 90 compiler is used by the **mpif90** command.

How the WRF build works:

There are two steps in building WRF: configuration and compilation.

Configuration: The **configure** script configures the model for compilation on your system. The configuration first attempts to locate needed libraries such as netCDF or HDF and tools such as Perl. It will check for these in normal places, or will use settings from the user's shell environment. The **configure** file then calls the UNIX **uname** command to discover what platform you are compiling on. It then calls the Perl script **arch/Config_new.pl**, which traverses the list of known machine configurations and displays a list of available options to the user. The selected set of options is then used to create the **configure.wrf** file in the top-level directory. This file may be edited but changes are temporary, since the file will be deleted by **clean –a** or overwritten by the next invocation of the **configure** script. About the only typical option that is included on the **configure** command is "**-d**" (for debug). The code builds relatively quickly and has the debugging switches enabled, but the model will run very slowly since all of the optimization has been deactivated. This script takes only a few seconds to run.

Compilation: The **compile** script is used to compile the WRF code after it has been configured using the **configure** script. This csh script performs a number of checks, constructs an argument list, copies to **Registry/Registry** the correct **Registry.*core*** file for the core being compiled, and the invokes the UNIX **make** command in the top-level directory. The core to be compiled is determined from the user's environment; if no core is specified in the environment (by setting **WRF_*core*_CORE** to **1**) the default core is selected (currently the Eulerian Mass core for ARW). The **Makefile** in the top-level directory directs the rest of the build, accomplished as a set of recursive invocations of **make** in the subdirectories of WRF. Most of these makefiles include the **configure.wrf** file from the top-level directory. The order of a complete build is as follows:

1. Make in **external** directory

    a. make in **external/io_{grib1,grib_share,int,netcdf}** for Grib Edition 1, binary, and netCDF implementations of I/O API

    b. make in **RSL_LITE** directory to build communications layer (DM_PARALLEL only)

   c. make in **`external/esmf_time_f90`** directory to build ESMF time manager library

   d. make in **`external/fftpack`** directory to build FFT library for the global filters

   e. make in other external directories as specified by "**`external:`**" target in the **`configure.wrf`** file

2. Make in the **`tools`** directory to build the program that reads the **`Registry/Registry`** file and auto-generates files in the **`inc`** directory

3. Make in the **`frame`** directory to build the WRF framework specific modules

4. Make in the **`share`** directory to build the non-core-specific mediation layer routines, including WRF I/O modules that call the I/O API

5. Make in the **`phys`** directory to build the WRF model layer routines for physics (non core-specific)

6. Make in the **`dyn_`*`core`*** directory for core-specific mediation-layer and model-layer subroutines

7. Make in the **`main`** directory to build the main programs for WRF, symbolic link to create executable files (location depending on the build case that was selected as the argument to the compile script)

Source files (**`.F`** and, in some of the external directories, **`.F90`**) are preprocessed to produce **`.f90`** files, which are input to the compiler. As part of the preprocessing, Registry-generated files from the **`inc`** directory may be included. Compiling the **`.f90`** files results in the creation of object (**`.o`**) files that are added to the library **`main/libwrflib.a`**. Most of the **`external`** directories generate their own library file. The linking step produces the **`wrf.exe`** executable and other executables, depending on the case argument to the compile command: **`real.exe`** (a preprocessor for real-data cases) or **`ideal.exe`** (a preprocessor for idealized cases), and the **`ndown.exe`** program, for one-way nesting of real-data cases.

The **`.o`** files and **`.f90`** files from a compile are retained until the next invocation of the **`clean`** script. The **`.f90`** files provide the true reference for tracking down run time errors that refer to line numbers or for sessions using interactive debugging tools such as **`dbx`** or **`gdb`**.

Registry

Tools for automatic generation of application code from user-specified tables provide significant software productivity benefits in development and maintenance of large

applications such as WRF. Just for the WRF model, some 250-thousand lines of WRF code are automatically generated from a user-edited table, called the Registry. The Registry provides a high-level single-point-of-control over the fundamental structure of the model data, and thus provides considerable utility for developers and maintainers. It contains lists describing state data fields and their attributes: dimensionality, binding to particular solvers, association with WRF I/O streams, communication operations, and run time configuration options (namelist elements and their bindings to model control structures). Adding or modifying a state variable to WRF involves modifying a single line of a single file; this single change is then automatically propagated to scores of locations in the source code the next time the code is compiled.

The WRF Registry has two components: the Registry file (which the user may edit), and the Registry program.

The Registry file is located in the **`Registry`** directory and contains the entries that direct the auto-generation of WRF code by the Registry program. There is more than one Registry in this directory, with filenames such as **`Registry.EM`** (for builds using the Eulerian Mass/ARW core) and **`Registry.NMM`** (for builds using the NMM core). The WRF Build Mechanism copies one of these to the file **`Registry/Registry`** and this file is used to direct the Registry program. The syntax and semantics for entries in the Registry are described in detail in "WRF Tiger Team Documentation: The Registry" on **`http://www.mmm.ucar.edu/wrf/WG2/Tigers/Registry/.`**
The Registry program is distributed as part of WRF in the **`tools`** directory. It is built automatically (if necessary) when WRF is compiled. The executable file is **`tools/registry`**. This program reads the contents of the Registry file, **`Registry/Registry`**, and generates files in the **`inc`** directory. These include files are inserted (with **`cpp #include`** commands) into WRF Fortran source files prior to compilation. Additional information on these is provided as an appendix to "WRF Tiger Team Documentation: The Registry (DRAFT)". The Registry program itself is written in C. The source files and **`makefile`** are in the **`tools`** directory.

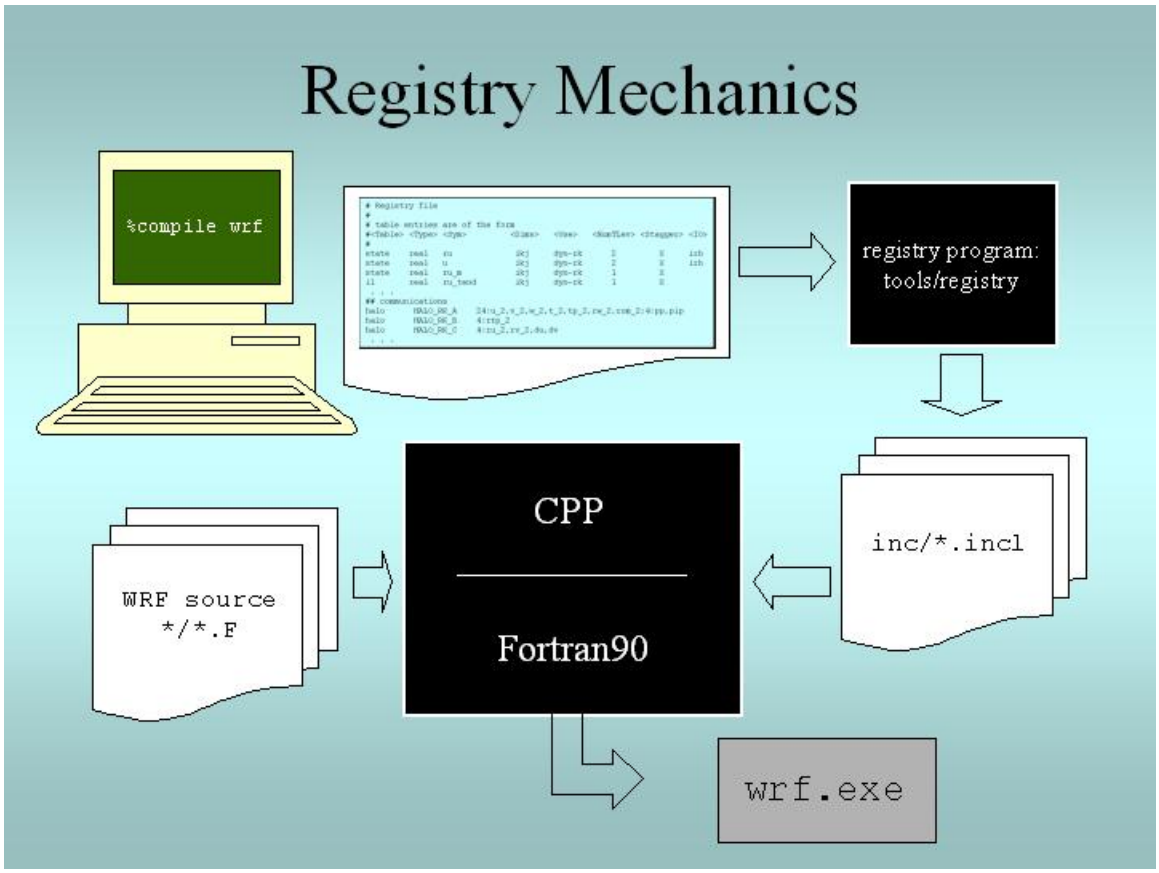


Figure 8.1. When the user compiles WRF, the Registry Program reads Registry/Registry, producing auto-generated sections of code that are stored in files in the **`inc`** directory. These are included into WRF using the CPP preprocessor and the Fortran compiler.

In addition to the WRF model itself, the **`Registry/Registry`** file is used to build the accompanying preprocessors such as **`real.exe`** (for real data) or **`ideal.exe`** (for ideal simulations), and the **`ndown.exe`** program (used for one-way, off-line nesting).

Every variable that is an input or an output field is described in the Registry. Additionally, every variable that is required for parallel communication, specifically associated with a physics package, or needs to provide a tendency to multiple physics or dynamics routines is contained in the Registry. For each of these variables, the index ordering, horizontal and vertical staggering, feedback and nesting interpolation requirements, and the associated IO are defined. For most users, to add a variable into the model requires, regardless of dimensionality, only the addition of a single line to the Registry (make sure that changes are made to the correct **`Registry.core`** file, as changes to the **`Registry`** file itself are overwritten). Since the Registry modifies code for compile-time options, and change to the Registry REQUIRES that the code be returned to the original unbuilt status with the **`clean -a`** command.

The other very typical activity for users is to define new run-time options, which are handled via a Fortran namelist file **`namelist.input`** in WRF. As with the model

state arrays and variables, the entire model configuration is described in the Registry. As with the model arrays, adding a new namelist entry is as easy as adding a new line in the Registry.

While the model state and configuration are by far the most commonly used features in the Registry, the data dictionary has several other powerful uses. The Registry file provides input to generate all of the communications for the distributed memory processing (halo interchanges between patches, support for periodic lateral boundaries, and array transposes for FFTs to be run in the X, Y, or Z directions). The Registry associates various fields with particular physics packages, so that the memory footprint reflects the actual selection of the options, not a maximal value.

Together, these capabilities allow a large portion of the WRF code to be automatically generated. Any code that is automatically generated relieves the developer of the effort of coding and debugging that portion of software. Usually, the pieces of code that are suitable candidates for automation are precisely those that are fraught with "hard to detect" errors, such as communications, indexing, and IO which must be replicated for hundreds of variables.

Registry Syntax:

Each entry in the Registry is for a specific variable, whether it is for a new dimension in the model, a new field, a new namelist value, or even a new communication. For readability, a single entry may be spread across several lines with the traditional "\" at the end of a line to denote that the entry is continuing. When adding to the Registry, most users find that it is helpful to copy an entry that is similar to the anticipated new entry, and then modify that Registry entry. The Registry is not sensitive to spatial formatting. White space separates identifiers in each entry.

Note: Do not simply remove an identifier and leave a supposed token blank, use the appropriate default value (currently a dash character "-").

Registry Entries:

The WRF Registry has the following types of entries (not case dependent):

Dimspec – Describes dimensions that are used to define arrays in the model
State – Describes state variables and arrays in the domain structure
I1 – Describes local variables and arrays in solve
Typedef – Describes derived types that are subtypes of the domain structure
Rconfig – Describes a configuration (e.g. namelist) variable or array
Package – Describes attributes of a package (e.g. physics)
Halo – Describes halo update interprocessor communications
Period – Describes communications for periodic boundary updates
Xpose – Describes communications for parallel matrix transposes
include – Similar to a CPP #include file

These ***keywords*** appear as the first word in a line of the file **`Registry`** to define which type of information is being provided. Following are examples of the more likely Registry types that users will need to understand.

Registry Dimspec:

The first set of entries in the Registry is the specifications of the dimensions for the fields to be defined. To keep the WRF system consistent between the dynamical cores and Chemistry, a unified **`registry.dimspec`** file is used (located in the **`Registry`** directory). This single file is included into each Registry file, with the keyword **`include`**. In the example below, three dimensions are defined: i, j, and k. If you do an "**`ncdump -h`**" on a WRF file, you will notice that the three primary dimensions are named as "**`west_east`**", "**`south_north`**", and "**`bottom_top`**". That information is contained in this example (the example is broken across two lines, but interleaved).

```
#<Table>  <Dim>  <Order> <How defined>
dimspec    i      1     standard_domain
dimspec    j      3     standard_domain
dimspec    k      2     standard_domain

<Coord-axis>  <Dimname in Datasets>
x           west_east
y           south_north
z           bottom_top
```

The WRF system has a notion of horizontal and vertical staggering, so the dimension names are extended with a **`"_stag`**" suffix for the staggered sizes. The list of names in the <Dim> column may either be a single unique character (for release 3.0.1.1 and prior), or the <Dim> column may be a string with no embedded spaces (such as **`my_dim`**). When this dimension is used later to dimension a **`state`** or **`i1`** variable, it must be surrounded by curly braces (such as **`{my_dim}`**). This <Dim> variable is not case specific, so for example "**i**" is the same as an entry for "**`I`**".

Registry State and I1:

A **`state`** variable in WRF is a field that is eligible for IO and communications, and exists for the duration of the model forecast. The **`I1`** variables (intermediate level one) are typically thought of as tendency terms, computed during a single model time-step, and then discarded prior to the next time-step. The space allocation and de-allocation for these **`I1`** variables is automatic (on the stack for the model solver). In this example, for readability, the column titles and the entries are broken into multiple interleaved lines, with the user entries in a **`bold font`**.

Some fields have simple entries in the **`Registry`** file. The following is a **`state`** variable that is a Fortran type **`real`**. The name of the field inside the WRF model is

u_gc. It is a three dimension array (**igj**). This particular field is only for the ARW core (**dyn_em**). It has a single time level, and is staggered in the **X** and **Z** directions. This field is input only to the real program (**i1**). On output, the netCDF name is **UU**, with the accompanying description and units provided.

```
#<Table> <Type> <Sym> <Dims>
state    real   u_gc   igj

<Use>  <NumTLev> <Stagger> <IO>
dyn_em     1          XZ     i1

<DNAME>  <DESCRIP>              <UNITS>
"UU"    "x-wind component"    "m s-1"
```

If a variable is not staggered, a "**-**" (dash) is inserted instead of leaving a blank space. The same dash character is required to fill in a location when a field has no IO specification. The variable description and units columns are used for post-processing purposes only; this information is not directly utilized by the model.

When adding new variables to the **Registry** file, users are warned to make sure that variable names are unique. The <Sym> refers to the variable name inside the WRF model, and it is not case sensitive. The <DNAME> is quoted, and appears exactly as typed. Do not use imbedded spaces. While it is not required that the <Sym> and <DNAME> use the same character string, it is highly recommended. The <DESCRIP> and the <UNITS> are optional, however they are a good way to supply self-documenation to the Registry. Since the <DESCRIP> value is used in the automatic code generation, restrict the variable description to 40 characters or less.

From this example, we can add new requirements for a variable. Suppose that the variable to be added is not specific to any dynamical core. We would change the <Use> column entry of **dyn_em** to **misc** (for miscellaneous). The **misc** entry is typical of fields used in physics packages. Only dynamics variables have more than a single time level, and this introductory material is not suitable for describing the impact of multiple time periods on the registry program. For the <Stagger> option, users may select any subset from {**X**, **Y**, **Z}** or **{-}**, where the dash character "**-**" signifies "no staggering". For example, in the ARW model, the x-direction wind component u is staggered in the **X** direction, and the y-direction wind component v is staggered in the **Y** direction.

The <IO> column handles file input and output, and it handles the nesting specification for the field. The file input and output uses three letters: **i** (input), **r** (restart), and **h** (history). If the field is to be in the input file to the model, the restart file from the model, and the history file from the model, the entry would be **irh**. To allow more flexibility, the input and history fields are associated with streams. The user may specify a digit after the **i** or the **h** token, stating that this variable is associated with a specified stream (**1** through **9**) instead of the default (**0**). A single variable may be associated with

multiple streams. Once any digit is used with the **i** or **h** tokens, the default **0** stream must be explicitly stated. For example, <IO> entry **i** and <IO> entry **i0** are the same. However, <IO> entry **h1** outputs the field to the first auxiliary stream, but does not output the field to the default history stream. The <IO> entry **h01** outputs the field to both the default history stream and the first auxiliary stream.

Nesting support for the model is also handled by the <IO> column. The letters that are parsed for nesting are: **u** (*up* as in feedback up), **d** (*down*, as in downscale from coarse to fine grid), **f** (*forcing*, how the lateral boundaries are processed), and **s** (*smoothing*). As with other entries, the best coarse of action is to find a field nearly identical to the one that you are inserting into the **Registry** file, and copy that line. The user needs to make the determination whether or not it is reasonable to smooth the field in the area of the coarse grid, where the fine-grid feeds back to the coarse grid. Variables that are defined over land and water, non-masked, are usually smoothed. The lateral boundary forcing is primarily for dynamics variables, and is ignored in this overview presentation. For non-masked fields (such as wind, temperature, pressure), the downward interpolation (controlled by **d**) and the feedback (controlled by **u**) use default routines. Variables that are land fields (such as soil temperature **TSLB**) or water fields (such as sea ice **XICE**) have special interpolators, as shown in the examples below (again, interleaved for readability):

```
#<Table> <Type> <Sym> <Dims>
state    real   TSLB   ilj
state    real   XICE   ij

<Use>  <NumTLev> <Stagger>
misc       1          Z
misc       1          -

<IO>
i02rhd=(interp_mask_land_field:lu_index)u=(copy_fcnm)
i0124rhd=(interp_mask_water_field:lu_index)u=(copy_fcnm)

<DNAME>  <DESCRIP>           <UNITS>
"TSLB"   "SOIL TEMPERATURE"   "K"
"SEAICE" "SEA ICE FLAG"       ""
```

Note that the **d** and **u** entries in the <IO> section are followed by an "**=**" then a parenthesis-enclosed subroutine, and a colon separated list of additional variables to pass to the routine. It is recommended that users follow the existing pattern: **du** for non-masked variables, and the above syntax for the existing interpolators for masked variables.

Registry Rconfig:

The **Registry** file is the location where the run-time options to configure the model are defined. Every variable in the ARW namelist is described by an entry in the **Registry** file. The default value for each of the namelist variables is as assigned in the Registry. The standard form for the entry for two namelist variables is given (broken across lines and interleaved):

```
#<Table>  <Type>    <Sym>
rconfig  integer    run_days
rconfig  integer    start_year

     <How set>           <Nentries>   <Default>
namelist,time_control      1            0
namelist,time_control  max_domains     1993
```

The keyword for this type of entry in the **Registry** file is **rconfig** (run-time configuration). As with the other model fields (such as **state** and **i1**), the <Type> column assigns the Fortran kind of the variable: **integer**, **real**, or **logical**. The name of the variable in ARW is given in the <Sym> column, and is part of the derived data type structure as are the **state** fields. There are a number of Fortran namelist records in the file **namelist.input**. Each namelist variable is a member of one of the specific namelist records. The previous example shows that **run_days** and **start_year** are both members of the **time_control** record. The <Nentries> column refers to the dimensionality of the namelist variable (number of entries). For most variables, the <Nentries> column has two eligible values, either **1** (signifying that the scalar entry is valid for all domains) or **max_domains** (signifying that the variable is an array, with a value specified for each domain). Finally, a default value is given. This permits a namelist entry to be removed from the **namelist.input** file if the default value is acceptable.

The registry program constructs two subroutines for each namelist variable, one to retrieve the value of the namelist variable, and the other to set the value. For an integer variable named **my_nml_var**, the following code snippet provides an example of the easy access to the namelist variables.

```
INTEGER :: my_nml_var, dom_id
CALL nl_get_my_nml_var ( dom_id , my_nml_var )
```

The subroutine takes two arguments. The first is the input integer domain identifier (for example, **1** for the most coarse grid, **2** for the second domain), and the second argument is the returned value of the namelist variable. The associated subroutine to set the namelist variable, with the same argument list, is **nl_set_my_nml_var**. For namelist variables that are scalars, the grid identifier should be set to **1**.

The **rconfig** line may also be used to define variables that are convenient to pass around in the model, usually part of a derived configuration (such as the number of microphysics species associated with a physics package). In this case, the <How set> column entry is **derived**. This variable does not appear in the namelist, but is accessible with the same generated **nl_set** and **nl_get** subroutines.

Registry Halo, Period, and Xpose:

The distributed memory, inter-processor communications are fully described in the **Registry** file. An entry in the Registry constructs a code segment which is included (with **cpp**) in the source code. Following is an example of a **halo** communication (split across two lines and interleaved for readability).

```
#<Table>  <CommName>   <Core>
halo      HALO_EM_D2_3 dyn_em

<Stencil:varlist>
24:u_2,v_2,w_2,t_2,ph_2;24:moist,chem,scalar;4:mu_2,al
```

The keyword is **halo**. The communication is named in the <CommName> column, so that it can be referenced in the source code. The entry in the <CommName> column is case sensitive (the convention is to start the name with **HALO_EM**). The selected dynamical core is defined in the <Core> column. There is no ambiguity, as every communication in each **Registry** file will have the exact same <Core> column option. The last set of information is the <Stencil:varlist>. The portion in front of the "**:**" is the stencil size, and the comma-separated list afterwards defines the variables that are communicated with that stencil size. Different stencil sizes are available, and are "**;**" separated in the same <Stencil:varlist> column. The stencil sizes **8**, **24**, **48** all refer to a square with an odd number of grid cells on a side, with the center grid cell removed (**8** = 3x3-1, **24** = 5x5-1, **48** = 7x7-1). The special small stencil **4** is just a simple north, south, east, west communication pattern.

The convention in the WRF model is to provide a communication immediately after a variable has been updated. The communications are restricted to the mediation layer (an intermediate layer of the software that is placed between the framework level and the model level. The model level is where developers spend most of their time. The majority of users will insert communications into the **dyn_em/solve_em.F** subroutine. The **HALO_EM_D2_3** communication defined in the **Registry** file, in the example above, is activated by inserting a small section of code that includes an automatically generated code segment into the solve routine, via standard **cpp** directives.

```
#ifdef DM_PARALLEL
#    include "HALO_EM_D2_3.inc"
#endif
```

The parallel communications are only required when the ARW code is built for distributed-memory parallel processing, which accounts for the surrounding **#ifdef**.

The **period** communications are required when periodic lateral boundary conditions are selected. The Registry syntax is very similar for **period** and **halo** communications, but the stencil size refers to how many grid cells to communicate, in a direction that is normal to the periodic boundary.

```
#<Table>     <CommName>          <Core>   <Stencil:varlist>
period   PERIOD_EM_COUPLE_A    dyn_em    2:mub,mu_1,mu_2
```

The **xpose** (a data transpose) entry is used when decomposed data is to be re-decomposed. This is required when doing FFTs in the x-direction for polar filtering, for example. No stencil size is necessary.

```
#<Table>     <CommName>          <Core>      <Varlist>
xpose    XPOSE_POLAR_FILTER_T  dyn_em   t_2,t_xxx,dum_yyy
```

It is anticipated that many users will add to the the parallel communications portion of the Registry file (**halo** and **period**. It is unlikely that users will add **xpose** fields.

Registry Package:

The **package** option in the **Registry** file associates fields with particular physics packages. Presently, it is mandatory that all 4-D arrays be assigned. Any 4-D array that is not associated with the selected physics option at run-time is neither allocated, used for IO, nor communicated. All other 2-D and 3-D arrays are eligible for use with a **package** assignment, but that is not required.

The purpose of the **package** option is to allow users to reduce the memory used by the model, since only "necessary" fields are processed. An example for a microphysics scheme is given below.

```
#<Table>  <PackageName>  <NMLAssociated>    <Variables>
package   kesslerscheme   mp_physics==1   - moist:qv,qc,qr
```

The entry keyword is **package**, and is associated with the single physics option listed under <NMLAssociated>. The package is referenced in the code in Fortran **IF** and **CASE** statements by the name given in the <PackageName> column, instead of the more confusing and typical **IF (mp_physics == 1)** approach. The <Variables> column must start with a dash character and then a blank "**- "** (for historical reasons of backward compatibility). The syntax of the <Variables> column then is a 4-D array name, followed by a colon, and then a comma-separated list of the 3-D arrays constituting that 4-D amalgamation. In the example above, the 4-D array is

moist, and the selected 3-D arrays are **qv**, **qc**, and **qr**. If more than one 4-D array is required, a "**;**" separates those sections from each other in the <Variables> column.

In addition to handling 4-D arrays and their underlying component 3-D arrays, the **package** entry is able to associate generic **state** variables, as shown in the example following. If the namelist variable **use_wps_input** is set to **1**, then the variables **u_gc** and **v_gc** are available to be processed.

```
#<Table>  <PackageName> <NMLAssociated>     <Variables>
package     realonly    use_wps_input==1  - state:u_gc,v_gc
```

I/O Applications Program Interface (I/O API)

The software that implements WRF I/O, like the software that implements the model in general, is organized hierarchically, as a "software stack" **(http://www.mmm.ucar.edu/wrf/WG2/Tigers/IOAPI/IOStack.html)**. From top (closest to the model code itself) to bottom (closest to the external package implementing the I/O), the I/O stack looks like this:

- Domain I/O (operations on an entire domain)
- Field I/O (operations on individual fields)
- Package-neutral I/O API
- Package-dependent I/O API (external package)

There is additional information on the WRF I/O software architecture on http://www.mmm.ucar.edu/wrf/WG2/IOAPI/IO_files/v3_document.htm. The lower-levels of the stack, associated with the interface between the model and the external packages, are described in the I/O and Model Coupling API specification document on **http://www.mmm.ucar.edu/wrf/WG2/Tigers/IOAPI/index.html**.

Timekeeping

Starting times, stopping times, and time intervals in WRF are stored and manipulated as Earth System Modeling Framework (ESMF, http://www.esmf.ucar.edu) time manager objects. This allows exact representation of time instants and intervals as integer numbers of years, months, hours, days, minutes, seconds, and fractions of a second (numerator and denominator are specified separately as integers). All time computations involving these objects are performed exactly by using integer arithmetic, with the result that there is no accumulated time step drift or rounding, even for fractions of a second.

The WRF implementation of the ESMF Time Manger is distributed with WRF in the **external/esmf_time_f90** directory. This implementation is entirely Fortran90 (as opposed to the ESMF implementation in C++) and it is conformant to the version of the ESMF Time Manager API that was available in 2009.

WRF source modules and subroutines that use the ESMF routines do so by use-association of the top-level ESMF Time Manager module, esmf_mod:

```
USE esmf_mod
```

The code is linked to the library file **`libesmf_time.a`** in the **`external/esmf_time_f90`** directory.

ESMF timekeeping is set up on a domain-by-domain basis in the routine setup_timekeeping (**`share/set_timekeeping.F`**). Each domain keeps track of its own clocks and alarms. Since the time arithmetic is exact there is no problem with clocks on separate domains getting out of synchronization.

Software Documentation

Detailed and comprehensive documentation aimed at WRF software is available at http://www.mmm.ucar.edu/wrf/WG2/software_2.0.

Performance

Benchmark information is available at http://www.mmm.ucar.edu/wrf/bench

Run-Time IO

With the release of WRF version 3.2, IO decisions may now be updated as a run-time option. Previously, any modification to the IO (such as which variable is associated with which stream) was handled via the Registry, and changes to the Registry always necessitate a cycle of **`clean -a`**, **`configure`**, and **`compile`**. This compile-time mechanism is still available and it is how most of the WRF IO is defined. However, should a user wish to add (or remove) variables from various streams, that capability is available as a option.

First, the user lets the WRF model know where the information for the run-time modifications to the IO is located. This is a single test file, defined in the **`namelist.input`** file, located in the **`time_control`** namelist record.

```
&time_control
iofields_filename = “my_file_d01.txt”, “my_file_d02.txt”
/
```

Each entry is associated with a specific domain ID, similar to the other multi-column entries in the WRF namelist file. The contents of the text file associates a stream ID (0 is

the default history and input) with a variable, and whether the field is to be added or removed. The state variables must already be defined in the Registry file. Following are a few examples:

`-:h:0:RAINC,RAINNC`
would remove the fields (case sensitive) RAINC and RAINNC from the standard history file.

`+:h:7:RAINC,RAINNC`
would add the fields RAINC and RAINNC to an output stream #6.

The available options are:

`+` or **`-`**, add or remove a variable
`0-24`, integer, which stream
`i` or **`h`**, input or history
field name in the Registry – this is the first string in quotes, case sensitive

It is not necessary to remove fields from one stream to insert them in another. It is OK to have the same field in multiple streams.

Chapter 9: Post-Processing Utilities

Table of Contents

Introduction

There are a number of visualization tools available to display WRF-ARW *(http://wrf-model.org/)* model data. Model data in netCDF format, can essentially be displayed using any tool capable of displaying this data format.

Currently the following post-processing utilities are supported, NCL, RIP4, ARWpost *(converter to GrADS)*, WPP, and VAPOR.

NCL, RIP4 and VAPOR can currently only read data in netCDF format, while ARWpost can read data in netCDF and GRIB1 *(limited functionality only for GRIB1)* format, and WPP can read data in netCDF and binary format.
Required software
The only library that is always required is the netCDF package from Unidata (***http://www.unidata.ucar.edu/***: login > Downloads > NetCDF - *registration login required*).

netCDF stands for **Net**work **C**ommon **D**ata **F**orm. This format is platform independent, i.e., data files can be read on both big-endian and little-endian computers, regardless of where the file was created. To use the netCDF libraries, ensure that the paths to these libraries are set correct in your login scripts as well as all Makefiles.

Additional libraries required by each of the supported post-processing packages:

- NCL (*http://www.ncl.ucar.edu*)
- GrADS (*http://grads.iges.org/home.html*)
- GEMPAK (*http://my.unidata.ucar.edu/content/software/gempak/index.html*)
- VAPOR (*http://www.vapor.ucar.edu*)

NCL

With the use of **NCL Libraries** *(http://www.ncl.ucar.edu)*, WRF-ARW data can easily be displayed.

The information on these pages has been put together to help users generate NCL scripts to display their WRF-ARW model data.

Some example scripts are available online (*http://www.mmm.ucar.edu/wrf/OnLineTutorial/Graphics/NCL/NCL_examples.htm*), but in order to fully utilize the functionality of the NCL Libraries, users should adapt these for their own needs, or write their own scripts.

NCL can process WRF ARW static, input and output files, as well as WRF-Var output data. Both single and double precision data can be processed.

WRF and NCL

In July 2007, the **WRF-NCL** processing scripts have been incorporated into the **NCL Libraries**, thus only the **NCL Libraries**, are now needed.

Major WRF ARW related upgrades have recently been added to the NCL libraries. In order to use many of the functions, NCL version 5.1.0 or higher is required *(current version of NCL is 5.2)*.

Special **functions** are provided to simplify the plotting of WRF ARW data.
These functions are located in
"$NCARG_ROOT/lib/ncarg/nclscripts/wrf/WRFUserARW.ncl".

Special **NCL built-in functions** have been added to the NCL libraries to help users calculate basic diagnostics for WRF ARW data.

All the **FORTRAN subroutines** used for diagnostics and interpolation *(previously located in wrf_user_fortran_util_0.f)* has been re-coded into NCL in-line functions. This means users no longer need to compile these routines.

What is NCL

The NCAR Command Language (NCL) is a free interpreted language designed specifically for scientific data processing and visualization. NCL has robust file input and output. It can read in netCDF, HDF4, HDF4-EOS, GRIB, binary and ASCII data. The graphics are world class and highly customizable.

It runs on many different operating systems including Solaris, AIX, IRIX, Linux, MacOSX, Dec Alpha, and Cygwin/X running on Windows. The NCL binaries are freely available at: *http://www.ncl.ucar.edu/Download/*

To read more about NCL, visit: *http://www.ncl.ucar.edu/overview.shtml*

Necessary software

NCL libraries *version 5.1.0 or higher (current version of NCL is 5.2).*

Environment Variable

Set the environment variable NCARG_ROOT to the location where you installed the NCL libraries. Typically *(for cshrc shell):*

```
setenv NCARG_ROOT /usr/local/ncl
```

.hluresfile

Create a file called **.hluresfile** in your $HOME directory. This file controls the color / background / fonts and basic size of your plot. For more information regarding this file, see: *http://www.ncl.ucar.edu/Document/Graphics/hlures.shtml*.

NOTE: *This file must reside in your $HOME directory and not where you plan on running NCL.*

Below is the **.hluresfile** used in the example scripts posted on the web *(scripts are available at: http://www.mmm.ucar.edu/wrf/users/graphics/NCL/NCL.htm*). If a different color table is used, the plots will appear different. Copy the following to your ~/.hluresfile. *(A copy of this file is available at: http://www.mmm.ucar.edu/wrf/OnLineTutorial/Graphics/NCL/.hluresfile)*

```
*wkColorMap : BlAqGrYeOrReVi200
*wkBackgroundColor : white
*wkForegroundColor : black
*FuncCode : ~
*TextFuncCode : ~
*Font : helvetica
*wkWidth : 900
*wkHeight : 900
```

NOTE:

If your image has a black background with white lettering, your .hluresfile has not been created correctly, or it is in the wrong location.

*wkColorMap, as set in your .hluresfile can be overwritten in any NCL script with the use of the function "**gsn_define_colormap**", so you do not need to change your .hluresfile if you just want to change the color map for a single plot.*

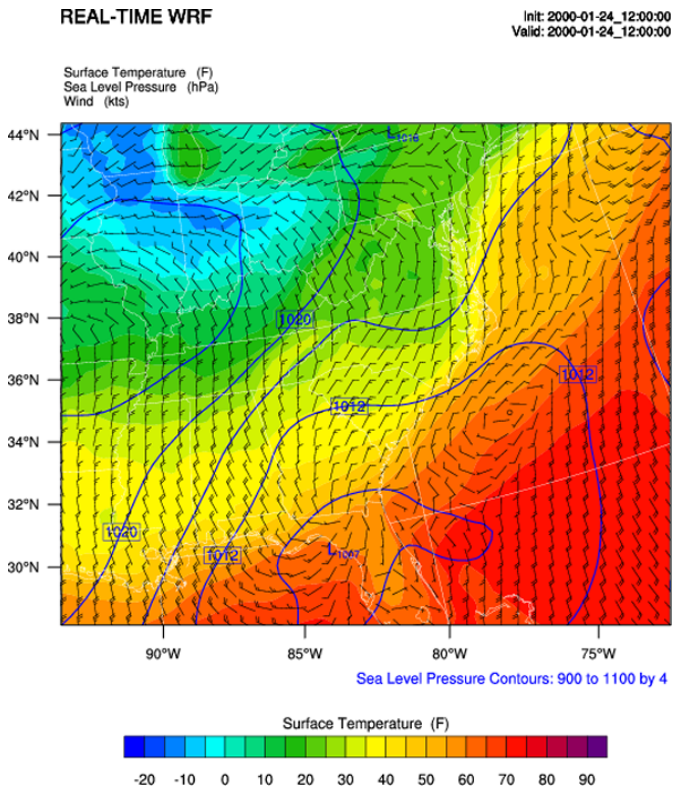
Create NCL scripts

The basic outline of any NCL script will look as follows:

```
load external functions and procedures

begin
      ; Open input file(s)
      ; Open graphical output
      ; Read variables
      ; Set up plot resources & Create plots
      ; Output graphics
end
```

For example, let's create a script to plot Surface Temperature, Sea Level Pressure and Wind as shown in the picture below.



```
; load functions and procedures
load "$NCARG_ROOT/lib/ncarg/nclscripts/csm/gsn_code.ncl"
load "$NCARG_ROOT/lib/ncarg/nclscripts/wrf/WRFUserARW.ncl"

begin

; WRF ARW input file
a = addfile("../wrfout_d01_2000-01-24_12:00:00.nc","r")


; Output on screen. Output will be called "plt_Surface1"
type = "x11"
wks = gsn_open_wks(type,"plt_Surface1")


; Set basic resources
res = True
res@MainTitle = "REAL-TIME WRF"          ; Give plot a main title
res@Footer = False                              ; Set Footers off
pltres = True                                 ; Plotting resources
mpres = True                                       ; Map resources

;---------------------------------------------------------------
times = wrf_user_list_times(a)             ; get times in the file
it = 0                               ; only interested in first time
res@TimeLabel = times(it)               ; keep some time information

;---------------------------------------------------------------
; Get variables

slp = wrf_user_getvar(a,"slp",it)                            Get slp
   wrf_smooth_2d( slp, 3 )                                ; Smooth slp

t2 = wrf_user_getvar(a,"T2",it)                    ; Get T2 (deg K)
   tc2 = t2-273.16                                 ; Convert to deg C
   tf2 = 1.8*tc2+32.                               ; Convert to deg F
   tf2@description = "Surface Temperature"
   tf2@units = "F"

u10 = wrf_user_getvar(a,"U10",it)                            ; Get U10
v10 = wrf_user_getvar(a,"V10",it)                            ; Get V10
   u10 = u10*1.94386                               ; Convert to knots
   v10 = v10*1.94386
   u10@units = "kts"
   v10@units = "kts"

;---------------------------------------------------------------
```

```
; Plotting options for T
opts = res                                      ; Add basic resources
opts@cnFillOn = True                                  ; Shaded plot
opts@ContourParameters = (/ -20., 90., 5./)    ; Contour intervals
opts@gsnSpreadColorEnd = -3
contour_tc = wrf_contour(a,wks,tf2,opts)              ; Create plot
delete(opts)


; Plotting options for SLP
opts = res                                      ; Add basic resources
opts@cnLineColor = "Blue"                          ; Set line color
opts@cnHighLabelsOn = True                          ; Set labels
opts@cnLowLabelsOn = True
opts@ContourParameters = (/ 900.,1100.,4./)    ; Contour intervals
contour_psl = wrf_contour(a,wks,slp,opts)             ; Create plot
delete(opts)


; Plotting options for Wind Vectors
opts = res                                      ; Add basic resources
opts@FieldTitle = "Winds"                 ; Overwrite the field title
opts@NumVectors = 47                         ; Density of wind barbs
vector = wrf_vector(a,wks,u10,v10,opts)               ; Create plot
delete(opts)


; MAKE PLOTS
plot = wrf_map_overlays(a,wks,  \
      (/contour_tc,contour_psl,vector/),pltres,mpres)

;---------------------------------------------------------------


end
```

Extra sample scripts are available at,
http://www.mmm.ucar.edu/wrf/OnLineTutorial/Graphics/NCL/NCL_examples.htm

Run NCL scripts

1. Ensure NCL is successfully installed on your computer.

2. Ensure that the environment variable NCARG_ROOT is set to the location where NCL is installed on your computer. Typically *(for cshrc shell)*, the command will look as follows:

```
setenv NCARG_ROOT /usr/local/ncl
```

3. Create an NCL plotting script.

4. Run the NCL script you created:

```
ncl  NCL_script
```

The output type created with this command is controlled by the line:
wks = gsn_open_wk (type,"Output") ; inside the NCL script
where *type* can be *x11, pdf, ncgm, ps,* or *eps*

For high quality images, create pdf / ps or eps images directly via the ncl scripts **(*type* = *pdf / ps / eps*)**

See the **Tools** section in Chapter 10 of this User's Guide for more information concerning other types of graphical formats and conversions between graphical formats.

Functions / Procedures under "$NCARG_ROOT/lib/ncarg/nclscripts/wrf/" *(WRFUserARW.ncl)*

wrf_user_getvar (*nc_file, fld, it*)
Usage: *ter = wrf_user_getvar (a, "HGT", 0)*

Get fields from netCDF file for any given time. Or all times by setting **it = -1**.

Any field available in the netCDF file can be extracted.
fld is case sensitive. The policy adapted during development was to set all diagnostic variables calculated by NCL to lower-case to distinguish them from fields directly available from the netCDF files.

List of available diagnostics:

avo	Absolute Vorticity [10-5 s-1]
pvo	Potential Vorticity [PVU]
cape_2d	Returns 2D fields mcape/mcin/lcl/lfc
cape_3d	Returns 3D fields cape/cin
dbz	Reflectivity [dBZ]
mdbz	Maximum Reflectivity [dBZ]
geopt/geopotential	Full Model Geopotential [m2 s-2]
lat	Latitude (will return either XLAT or XLAT_M, depending on which is available)
lon	Longitude (will return either XLONG or XLONG_M, depending on which is available)
p/pres	Full Model Pressure [Pa]

pressure	Full Model Pressure [hPa]
rh2	2m Relative Humidity [%]
rh	Relative Humidity [%]
slp	Sea Level Pressure [hPa]
ter	Model Terrain Height [m] (will return either HGT or HGT_M, depending on which is available)
td2	2m Dew Point Temperature [C]
td	Dew Point Temperature [C]
tc	Temperature [C]
tk	Temperature [K]
th/theta	Potential Temperature [K]
ua	U component of wind on mass points
va	V component of wind on mass points
wa	W component of wind on mass points
uvmet10	10m U and V components of wind rotated to earth coordinates
uvmet	U and V components of wind rotated to earth coordinates
z/height	Full Model Height [m]

wrf_user_list_times (*nc_file*)
Usage: *times* = wrf_user_list_times *(a)*

Obtain a list of times available in the input file. The function returns a 1D array containing the times *(type: character)* in the input file.

wrf_contour (*nc_file, wks, data, res*)
Usage: *contour* = wrf_contour *(a, wks, ter, opts)*

Returns a graphic (*contour*), of the ***data*** to be contoured. This graphic is only created, but not plotted to a wks. This enables a user to generate many such graphics and overlay them before plotting the resulting picture to a wks.

The returned graphic (*contour*) does not contain map information, and can therefore be used for both real and idealized data cases.

This function can plot both line contours and shaded contours. *Default is line contours.*

Many resources are set for a user, of which most can be overwritten. Below is a list of resources you may want to consider changing before generating your own graphics:

Resources unique to ARW WRF Model data
opts@MainTitle : Controls main title on the plot.
opts@MainTitlePos : Main title position – Left/Right/Center. Default is Left.
opts@NoHeaderFooter : Switch off all Headers and Footers.
opts@Footer : Add some model information to the plot as a footer. Default is True.
opts@InitTime : Plot initial time on graphic. Default is True. If True, the initial time will be extracted from the input file.
opts@ValidTime : Plot valid time on graphic. Default is True. A user must set opts@TimeLabel to the correct time.
opts@TimeLabel : Time to plot as valid time.
opts@TimePos : Time position – Left/Right. Default is "Right".
opts@ContourParameters : A single value is treated as an interval. Three values represent: Start, End, and Interval.
opts@FieldTitle : Overwrite the field title - if not set the field description is used for the title.
opts@UnitLabel : Overwrite the field units - seldom needed as the units associated with the field will be used.
opts@PlotLevelID : Use to add level information to the field title.

General NCL resources *(most standard NCL options for cn and lb can be set by the user to overwrite the default values)*
opts@cnFillOn : Set to True for shaded plots. Default is False.
opts@cnLineColor : Color of line plot.
opts@lbTitleOn : Set to False to switch the title on the label bar off. Default is True.
opts@cnLevelSelectionMode ; *opts @cnLevels* ; *opts@cnFillColors* ;
optr@cnConstFLabelOn : Can be used to set contour levels and colors manually.

wrf_vector (*nc_file, wks, data_u, data_v, res*)
Usage: *vector* = wrf_vector *(a, wks, ua, va, opts)*

Returns a graphic (*vector*) of the data. This graphic is only created, but not plotted to a wks. This enables a user to generate many graphics and overlay them before plotting the resulting picture to a wks.

The returned graphic (*vector*) does not contain map information, and can therefore be used for both real and idealized data cases.

Many resources are set for a user, of which most can be overwritten. Below is a list of resources you may want to consider changing before generating your own graphics:

Resources unique to ARW WRF Model data
opts@MainTitle : Controls main title on the plot.
opts@MainTitlePos : Main title position – Left/Right/Center. Default is Left.
opts@NoHeaderFooter : Switch off all Headers and Footers.

opts@Footer : Add some model information to the plot as a footer. Default is True.
opts@InitTime : Plot initial time on graphic. Default is True. If True, the initial time will be extracted from the input file.
opts@ValidTime : Plot valid time on graphic. Default is True. A user must set opts@TimeLabel to the correct time.
opts@TimeLabel : Time to plot as valid time.
opts@TimePos : Time position – Left/Right. Default is "Right".
opts@ContourParameters : A single value is treated as an interval. Three values represent: Start, End, and Interval.
opts@FieldTitle : Overwrite the field title - if not set the field description is used for the title.
opts@UnitLabel : Overwrite the field units - seldom needed as the units associated with the field will be used.
opts@PlotLevelID : Use to add level information to the field title.
opts@NumVectors : Density of wind vectors.

General NCL resources *(most standard NCL options for vc can be set by the user to overwrite the default values)*
opts@vcGlyphStyle : Wind style. "WindBarb" is default.

wrf_map_overlays (*nc_file, wks, (/graphics/), pltres, mpres*)
Usage: *plot = wrf_map_overlays (a, wks, (/contour,vector/), pltres, mpres)*

Overlay contour and vector plots generated with *wrf_contour* and *wrf_vector*. Can overlay any number of graphics. Overlays will be done in order give, so always list shaded plots before line or vector plots, to ensure the lines and vectors are visible and not hidden behind the shaded plot.

A map background will automatically be added to the plot. Map details are controlled with the *mpres* resource. Common map resources you may want to set are:
mpres@mpGeophysicalLineColor ; mpres@mpNationalLineColor ;
mpres@mpUSStateLineColor ; mpres@mpGridLineColor ;
mpres@mpLimbLineColor ; mpres@mpPerimLineColor

If you want to zoom into the plot, set *mpres@ZoomIn* to True, and *mpres@Xstart, mpres@Xend, mpres@Ystart, mpres@Yend*, to the corner x/y positions of the zoomed plot.

pltres@NoTitles : Set to True to remove all field titles on a plot.
pltres@CommonTitle : Overwrite field titles with a common title for the overlaid plots. Must set *pltres@PlotTitle* to desired new plot title.

If you want to generate images for a panel plot, set *pltres@PanelPot* to True.

If you want to add text/lines to the plot before advancing the frame, set *pltres@FramePlot* to False. Add your text/lines directly after the call to the *wrf_map_overlays* function. Once you are done adding text/lines, advance the frame with the command "***frame (wks)***".

wrf_overlays (nc_file*, wks, (/graphics/), pltres*)
Usage: *plot = wrf_overlays (a, wks, (/contour,vector/), pltres)*

Overlay contour and vector plots generated with *wrf_contour* and *wrf_vector*. Can overlay any number of graphics. Overlays will be done in order give, so always list shaded plots before line or vector plots, to ensure the lines and vectors are visible and not hidden behind the shaded plot.

Typically used for idealized data or cross-sections, which does not have map background information.

pltres@NoTitles : Set to True to remove all field titles on a plot.
pltres@CommonTitle : Overwrite field titles with a common title for the overlaid plots. Must set *pltres@PlotTitle* to desired new plot title.

If you want to generate images for a panel plot, set *pltres@PanelPot* to True.

If you want to add text/lines to the plot before advancing the frame, set *pltres@FramePlot* to False. Add your text/lines directly after the call to the *wrf_overlays* function. Once you are done adding text/lines, advance the frame with the command "***frame (wks)***".

wrf_map (*nc_file, wks, res*)
Usage: *map = wrf_map (a, wks, opts)*

Create a map background.
As maps are added to plots automatically via the *wrf_map_overlays* function, this function is seldom needed as a stand-alone.

wrf_user_intrp3d (*var3d, H, plot_type, loc_param, angle, res*)

This function is used for both horizontal and vertical interpolation.

var3d: The variable to interpolate. This can be a array of up to 5 dimensions. The 3 right-most dimensions must be *bottom_top x south_north x west_east*.

H: The field to interpolate to. Either pressure *(hPa or Pa)*, or z *(m)*. Dimensionality must match **var3d**.
plot_type: "h" for horizontally and "v" for vertically interpolated plots.
loc_param: Can be a scalar, or an array holding either 2 or 4 values.
For plot_type = "h":
This is a scalar representing the level to interpolate too.
Must match the field to interpolate too (H).
When interpolating to pressure, this can be in hPa or Pa *(e.g. 500., to interpolate to 500 hPa)*. When interpolating to height this must in in *m (e.g. 2000., to interpolate to 2 km)*.
For plot_type = "v":
This can be a pivot point though which a line is drawn – in this case a single x/y point *(2 values)* is required. Or this can be a set of x/y points *(4 values)*, indicating start x/y and end x/y locations for the cross-section.
angle:
Set to 0., for *plot_type = "h"*, or *for plot_type = "v"* when start and end locations of cross-section were supplied in *loc_param*.
If a single pivot point was supplied in *loc_param*, angle is the angle of the line that will pass through the pivot point. Where: 0. is SN, and 90. is WE.
res:
Set to False for *plot_type = "h"*, or for *plot_type = "v"* when a single pivot point is supplied. Set to True if start and end locations are supplied.

wrf_user_intrp2d (*var2d, loc_param, angle, res*)

This function interpolates a 2D field along a given line.

var2d: Is the 2D field to interpolate. This can be a array of up to 3 dimensions. The 2 right-most dimensions must be *south_north x west_east*.
loc_param:
An array holding either 2 or 4 values.
This can be a pivot point though which a line is drawn - in this case a single x/y point *(2 values)* is required. Or this can be a set of x/y points *(4 values)*, indicating start x/y and end x/y locations for the cross-section.
angle:
Set to 0 when start and end locations of the line was supplied in *loc_param*.
If a single pivot point was supplied in *loc_param*, angle is the angle of the line that will pass through the pivot point. Where: 0. is SN, and 90. is WE.
res:
Set to False when a single pivot point is supplied. Set to True if start and end locations is supplied.

wrf_user_ll_to_ij (nc_file, lons, lats, res)
Usage: *loc = wrf_user_latlon_to_ij (a, 100., 40., res)*
Usage: *loc = wrf_user_latlon_to_ij (a, (/100., 120./), (/40., 50./), res)*

Convert a lon/lat location to the nearest x/y location. This function makes use of map information to find the closest point, so this returned value may potentially be outside the model domain.

lons/lats can be scalars or arrays.

Optional resources:
res@returnInt - If set to False, the return values will be real (default is True with integer return values)
res@useTime - Default is 0. Set if want the reference longitude/latitudes must come from a specific time - one will only use this for moving nest output which has been stored in a single file.

loc(0,:) is the x (WE) locations, and loc(1,:) the y (SN) locations.

wrf_user_ij_to_ll (nc_file, i, j, res)
Usage: *loc = wrf_user_latlon_to_ij (a, 10, 40, res)*
Usage: *loc = wrf_user_latlon_to_ij (a, (/10, 12/), (/40, 50/), res)*

Convert a i/j location to a lon/lat location. This function makes use of map information to find the closest point, so this returned value may potentially be outside the model domain.

i/j can be scalars or arrays.

Optional resources:
res@useTime - Default is 0. Set if want the reference longitude/latitudes must come from a specific time - one will only use this for moving nest output which has been stored in a single file.

loc(0,:) is the lons locations, and loc(1,:) the lats locations.

wrf_user_unstagger (varin, unstagDim)

This function unstaggers an array. This function returns an array on ARW WRF mass points.

varin: Array to be unstaggered.

unstagDim: Dimension to unstagger. Must be either "X", "Y", or "Z". This is case sensitive. If not one of these strings, the returning array will be unchanged.

wrf_wps_dom (wks, mpres, lnres, txres)

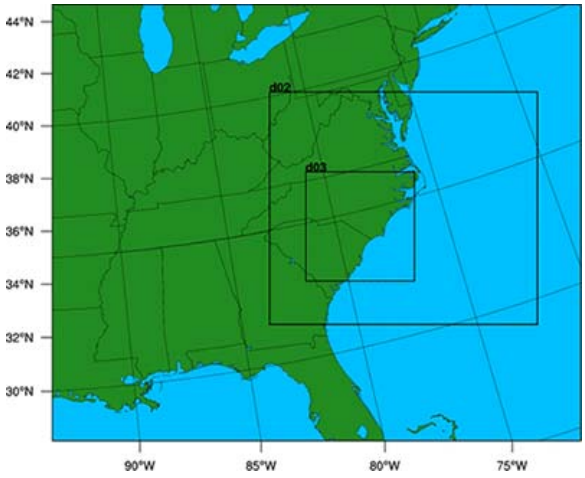
A function has been built into NCL to preview where a potential domain will be placed *(similar to plotgrids.exe from WPS).*

The lnres and txres resources are standard NCL Line and Text resources. These are used to add nests to the preview.

The mpres are used for standard map background resources like:
mpres@mpFillOn ; mpres@mpFillColors ; mpres@mpGeophysicalLineColor ; mpres@mpNationalLineColor ; mpres@mpUSStateLineColor ; mpres@mpGridLineColor ; mpres@mpLimbLineColor ; mpres@mpPerimLineColor

But its main function is to set map resources to preview a domain. These resources are similar to the resources set in WPS. Below is an example to display 3 nested domains on a Lambert projection. *(The output is shown below).*

```
mpres@max_dom           = 3
mpres@parent_id         = (/ 1,    1,   2 /)
mpres@parent_grid_ratio = (/ 1,    3,   3 /)
mpres@i_parent_start    = (/ 1,   31,  15 /)
mpres@j_parent_start    = (/ 1,   17,  20 /)
mpres@e_we              = (/ 74, 112, 133/)
mpres@e_sn              = (/ 61,  97, 133 /)
mpres@dx                = 30000.
mpres@dy                = 30000.
mpres@map_proj          = "lambert"
mpres@ref_lat           = 34.83
mpres@ref_lon           = -81.03
mpres@truelat1          = 30.0
mpres@truelat2          = 60.0
mpres@stand_lon         = -98.0
```



NCL built-in Functions

A number of NCL built-in functions have been created to help users calculate simply diagnostics. Full descriptions of these functions are available on the NCL web site (http://www.ncl.ucar.edu/Document/Functions/wrf.shtml).

wrf_avo	Calculates absolute vorticity.
wrf_cape_2d	Computes convective available potential energy (CAPE), convective inhibition (CIN), lifted condensation level (LCL), and level of free convection (LFC).
wrf_cape_3d	Computes convective available potential energy (CAPE) and convective inhibition (CIN).
wrf_dbz	Calculates the equivalent reflectivity factor.
wrf_eth	Calculates equivalent potential temperature
wrf_helicity	Calculates storm relative helicity
wrf_ij_to_ll	Finds the longitude, latitude locations to the specified model grid indices (i,j).
wrf_ll_to_ij	Finds the model grid indices (i,j) to the specified location(s) in longitude and latitude.
wrf_pvo	Calculates potential vorticity.
wrf_rh	Calculates relative humidity.
wrf_slp	Calculates sea level pressure.
wrf_smooth_2d	Smooth a given field.
wrf_td	Calculates dewpoint temperature in [C].
wrf_tk	Calculates temperature in [K].
wrf_updraft_helicity	Calculates updraft helicity
wrf_uvmet	Rotates u,v components of the wind to earth coordinates.

Adding diagnostics using FORTRAN code

It is possible to link your favorite FORTRAN diagnostics routines to NCL. It is easier to use FORTRAN 77 code, but NCL does recognize basic FORTRAN 90 code.

Let's use a routine that calculated temperature (K) from theta and pressure.

FORTRAN 90 routine called myTK.f90

```
subroutine compute_tk (tk, pressure, theta, nx, ny, nz)
implicit none

!! Variables
   integer  :: nx, ny, nz
   real, dimension (nx,ny,nz) :: tk, pressure, theta

!! Local Variables
   integer :: i, j, k
   real, dimension (nx,ny,nz):: pi

   pi(:,:,:) = (pressure(:,:,:) / 1000.)**(287./1004.)
   tk(:,:,:) = pi(:,:,:)*theta(:,:,:)

return
end subroutine compute_tk
```

For simple routines like this, it is easiest to re-write the routine into a FORTRAN 77 routine.

FORTRAN 77 routine called myTK.f

```
      subroutine compute_tk (tk, pressure, theta, nx, ny, nz)
      implicit none

C     Variables
      integer  nx, ny, nz
      real   tk(nx,ny,nz) , pressure(nx,ny,nz), theta(nx,ny,nz)

C     Local Variables
      integer  i, j, k
      real   pi

      DO k=1,nz
        DO j=1,ny
          DO i=1,nx
            pi=(pressure(i,j,k) / 1000.)**(287./1004.)
            tk(i,j,k) = pi*theta(i,j,k)
          ENDDO
        ENDDO
      ENDDO

     return
     end
```

Add the markers **NCLFORTSTART** and **NCLEND** to the subroutine as indicated below. Note, that local variables are outside these block markers.

FORTRAN 77 routine called myTK.f, with NCL markers added

```
C NCLFORTSTART
      subroutine compute_tk (tk, pressure, theta, nx, ny, nz)
      implicit none

C     Variables
      integer  nx, ny, nz
      real   tk(nx,ny,nz) , pressure(nx,ny,nz), theta(nx,ny,nz)

C NCLEND

C     Local Variables
      integer  i, j, k
      real   pi

      DO k=1,nz
        DO j=1,ny
          DO i=1,nx
            pi=(pressure(i,j,k) / 1000.)**(287./1004.)
            tk(i,j,k) = pi*theta(i,j,k)
          ENDDO
        ENDDO
      ENDDO

    return
    end
```

Now compile this code using the NCL script WRAPIT.

```
WRAPIT myTK.f
```

NOTE: If WRAPIT cannot be found, make sure the environment variable *NCARG_ROOT* has been set correctly.

If the subroutine compiles successfully, a new library will be created, called **myTK.so.** This library can be linked to an NCL script to calculate TK. See how this is done in the example below:

```
load "$NCARG_ROOT/lib/ncarg/nclscripts/csm/gsn_code.ncl"
load "$NCARG_ROOT/lib/ncarg/nclscripts/wrf/WRFUserARW.ncl"
external myTK "./myTK.so"

begin

        t = wrf_user_getvar (a,"T",5)
        theta = t + 300
        p = wrf_user_getvar (a,"pressure",5)
```

```
        dim = dimsizes(t)
        tk = new( (/ dim(0), dim(1), dim(2) /), float)

      myTK :: compute_tk (tk, p, theta, dim(2), dim(1), dim(0))

end
```

Want to use the FORTRAN 90 program? It is possible to do so by providing an interface block for your FORTRAN 90 program. Your FORTRAN 90 program may also not contain any of the following features:

- pointers or structures as arguments,
- missing/optional arguments,
- keyword arguments, or
- if the procedure is recursive.

Interface block for FORTRAN 90 code, called myTK90.stub

```
C NCLFORTSTART
      subroutine compute_tk (tk, pressure, theta, nx, ny, nz)

      integer  nx, ny, nz
      real   tk(nx,ny,nz) , pressure(nx,ny,nz), theta(nx,ny,nz)

C NCLEND
```

Now compile this code using the NCL script WRAPIT.

```
WRAPIT myTK90.stub myTK.f90
```

NOTE: You may need to copy the WRAPIT script to a locate location and edit it to point to a FORTRAN 90 compiler.

If the subroutine compiles successfully, a new library will be created, called **myTK90.so** *(note the change in name from the FORTRAN 77 library).* This library can similarly be linked to an NCL script to calculate TK. See how this is done in the example below:

```
load "$NCARG_ROOT/lib/ncarg/nclscripts/csm/gsn_code.ncl"
load "$NCARG_ROOT/lib/ncarg/nclscripts/wrf/WRFUserARW.ncl"
external myTK90 "./myTK90.so"

begin
        t = wrf_user_getvar (a,"T",5)
        theta = t + 300
        p = wrf_user_getvar (a,"pressure",5)

        dim = dimsizes(t)
        tk = new( (/ dim(0), dim(1), dim(2) /), float)

      myTK90 :: compute_tk (tk, p, theta, dim(2), dim(1), dim(0))

end
```

RIP4

RIP (which stands for Read/Interpolate/Plot) is a Fortran program that invokes NCAR Graphics routines for the purpose of visualizing output from gridded meteorological data sets, primarily from mesoscale numerical models. It was originally designed for sigma-coordinate-level output from the PSU/NCAR Mesoscale Model (MM4/MM5), but was generalized in April 2003 to handle data sets with any vertical coordinate, and in particular, output from the Weather Research and Forecast (WRF) modeling system. It can also be used to visualize model input or analyses on model grids. It has been under continuous development since 1991, *primarily by Mark Stoelinga at both NCAR and the University of Washington.*

The RIP **users' guide** (*http://www.mmm.ucar.edu/wrf/users/docs/ripug.htm*) is essential reading.

Code history

Version 4.0: reads WRF-ARW real output files
Version 4.1: reads idealized WRF-ARW datasets
Version 4.2: reads all the files produced by WPS
Version 4.3: reads files produced by WRF-NMM model
Version 4.4: add ability to output different graphical types
Version 4.5: add configure/compiler capabilities
Version 4.6: current version – only bug fix changes between 4.5 and 4.6
(This document will only concentrate on running RIP4 for WRF-ARW. For details on running RIP4 for WRF-NMM, see the WRF-NMM User's Guide: http://www.dtcenter.org/wrf-nmm/users/docs/user_guide/V3/index.htm)

Necessary software

RIP4 only requires low level NCAR Graphics libraries. These libraries have been merged with the NCL libraries since the release of NCL version 5 (*http://www.ncl.ucar.edu/*), so if you don't already have NCAR Graphics installed on your computer, install NCL version 5.

Obtain the code from the WRF-ARW user's web site:
http://www.mmm.ucar.edu/wrf/users/download/get_source.html

Unzip and untar the RIP4 tar file. The tar file contains the following directories and files:

- *CHANGES*, a text file that logs changes to the RIP tar file.
- *Doc/*, a directory that contains documentation of RIP, most notably the Users' Guide (*ripug*).

- *README*, a text file containing basic information on running RIP.
- *arch/*, directory containing the default compiler flags for different machines.
- *clean*, script to clean compiled code.
- *compile*, script to compile code.
- *configure*, script to create a configure file for your machine.
- *color.tbl*, a file that contains a table defining the colors you want to have available for RIP plots.
- *eta_micro_lookup.dat*, a file that contains "look-up" table data for the Ferrier microphysics scheme.
- *psadilookup.dat*, a file that contains "look-up" table data for obtaining temperature on a pseudoadiabat.
- *sample_infiles/*, a directory that contains sample user input files for RIP and related programs.
- *src/*, a directory that contains all of the source code files for RIP, RIPDP, and several other utility programs.
- *stationlist*, a file containing observing station location information.

Environment Variables

An important environment variable for the RIP system is **RIP_ROOT**.
RIP_ROOT should be assigned the path name of the directory where all your RIP program and utility files (*color.tbl*, *stationlist*, lookup tables, etc.) reside.
Typically *(for cshrc shell):*

```
setenv RIP_ROOT /my-path/RIP4
```

The RIP_ROOT environment variable can also be overwritten with the variable *rip_root* in the RIP user input file (UIF).

A second environment variable you need to set is **NCARG_ROOT**.
Typically *(for cshrc shell):*

```
setenv NCARG_ROOT /usr/local/ncarg     ! for NCARG V4
setenv NCARG_ROOT /usr/local/ncl       ! for NCL V5
```

Compiling RIP and associated programs

Since the release of version 4.5, the same configure/compile scripts available in all other WRF programs have been added to RIP4. To compile the code, first configure for your machine by typing:

```
./configure
```

You will see a list of options for your computer *(below is an example for a Linux machine)*:

```
Will use NETCDF in dir: /usr/local/netcdf-pgi
------------------------------------------------------------
Please select from among the following supported platforms.
1.  PC Linux i486 i586 i686 x86_64, PGI compiler
2.  PC Linux i486 i586 i686 x86_64, g95 compiler
3.  PC Linux i486 i586 i686 x86_64, gfortran compiler
4.  PC Linux i486 i586 i686 x86_64, Intel compiler

Enter selection [1-4]
```

Make sure the netCDF path is correct.
Pick compile options for your machine.

This will create a file called `configure.rip`. Edit compile options/paths, if necessary.

To compile the code, type:

```
./compile
```

After a successful compilation, the following new files should be created.

rip	RIP post-processing program. Before using this program, first convert the input data to the correct format expected by this program, using the program ripdp
ripcomp	This program reads in two rip data files and compares their contents.
ripdp_mm5	RIP Data Preparation program for MM5 data
ripdp_wrfarw **ripdp_wrfnmm**	RIP Data Preparation program for WRF data
ripinterp	This program reads in model output (in rip-format files) from a coarse domain and from a fine domain, and creates a new file which has the data from the coarse domain file interpolated (bi-linearly) to the fine domain. The header and data dimensions of the new file will be that of the fine domain, and the case name used in the file name will be the same as that of the fine domain file that was read in.
ripshow	This program reads in a rip data file and prints out the contents of the header record.
showtraj	Sometimes, you may want to examine the contents of a trajectory position file. Since it is a binary file, the trajectory position file cannot simply be printed out. showtraj, reads the trajectory position file and prints out its contents in a readable form. When you run

	showtraj, it prompts you for the name of the trajectory position file to be printed out.
tabdiag	If fields are specified in the plot specification table for a trajectory calculation run, then RIP produces a .diag file that contains values of those fields along the trajectories. This file is an unformatted Fortran file; so another program is required to view the diagnostics. tabdiag serves this purpose.
upscale	This program reads in model output (in rip-format files) from a coarse domain and from a fine domain, and replaces the coarse data with fine data at overlapping points. Any refinement ratio is allowed, and the fine domain borders do not have to coincide with coarse domain grid points.

Preparing data with RIPDP

RIP does not ingest model output files directly. First, a preprocessing step must be executed that converts the model output data files to RIP-format data files. The primary difference between these two types of files is that model output data files typically contain all times and all variables in a single file (or a few files), whereas RIP data has each variable at each time in a separate file. The preprocessing step involves use of the program RIPDP (which stands for RIP Data Preparation). RIPDP reads in a model output file (or files), and separates out each variable at each time.

Running RIPDP

The program has the following usage:

```
ripdp_XXX [-n namelist_file] model-data-set-name [basic|all]
data_file_1 data_file_2 data_file_3 ...
```

In the above, the "XXX" refers to "mm5", "wrfarw", or "wrfnmm".
The argument model-data-set-name can be any string you choose, that uniquely defines this model output data set

The use of the namelist file is optional. The most important information in the namelist, is the times you want to process.

As this step will create a large number of extra files, creating a new directory to place these files in, will enable you to manage the files easier ***(`mkdir RIPDP`)*.**

e.g. `ripdp_wrfarw RIPDP/arw all wrfout_d01_*`

The RIP user input file

Once the RIP data has been created with RIPDP, the next step is to prepare the user input file (UIF) for RIP *(see Chapter 4 of the RIP users' guide for details)*. This file is a text file, which tells RIP what plots you want and how they should be plotted. A sample UIF, called *rip_sample.in*, is provided in the RIP tar file. This sample can serve as a template for the many UIFs that you will eventually create.

A UIF is divided into two main sections. The first section specifies various general parameters about the set up of RIP, in a namelist format (***userin*** - *which control the general input specifications; and* ***trajcalc*** - *which control the creation of trajectories*). The second section is the plot specification section, which is used to specify which plots will be generated.

namelist: userin

Variable	Value	Description
idotitle	1	Control first part of title.
title	'auto'	Define your own title, or allow RIP to generate one.
titlecolor	'def.foreground'	Control color of the title.
iinittime	1	Print initial date and time *(in UTC)* on plot.
ifcsttime	1	Print forecast lead-time *(in hours)* on plot.
ivalidtime	1	Print valid date and time (*in both UTC and local time*) on plot.
inearesth	0	This allows you to have the hour portion of the initial and valid time be specified with two digits, rounded to the nearest hour, rather than the standard 4-digit HHMM specification.
timezone	-7.0	Specifies the offset from Greenwich time.
iusdaylightrule	1	Flag to determine if US daylight saving should be applied.
ptimes	9.0E+09	Times to process. This can be a string of times *(e.g. 0,3,6,9,12,)* or a series in the form of *A,-B,C,* which means "times from hour *A*, to hour *B*, every *C* hours" *(e.g. 0,-12,3,).* Either *ptimes* or *iptimes* can be used, but not both. *You can plot all available times, by omitting both ptimes and iptimes from the namelist, or by setting the first value negative.*
ptimeunits	'h'	Time units. This can be 'h' *(hours)*, 'm' *(minutes)*, or 's' *(seconds). Only valid with ptimes.*
iptimes	99999999	Times to process. This is an integer array that specifies desired times for RIP to plot, but in the form of 8-digit

		"mdate" times *(i.e. YYMMDDHH)*. Either *ptimes* or *iptimes* can be used, but not both. *You can plot all available times, by omitting both ptimes and iptimes from the namelist, or by setting the first value negative*.
tacc	1.0	Time tolerance in seconds. Any time in the model output that is within *tacc* seconds of the time specified in *ptimes/iptimes* will be processed.
flmin, flmax, *fbmin, ftmax*	.05, .95, .10, .90	Left, right, bottom and top frame limit
ntextq	0	Text quality specifier (0=high; 1=medium; 2=low).
ntextcd	0	Text font specifier [0=complex (Times); 1=duplex (Helvetica)].
fcoffset	0.0	This is an optional parameter you can use to "tell" RIP that you consider the start of the forecast to be different from what is indicated by the forecast time recorded in the model output. Examples: *fcoffset*=12 means you consider hour 12 in the model output to be the beginning of the true forecast.
idotser	0	Generate time series output files *(no plots)* only an ASCII file that can be used as input to a plotting program.
idescriptive	1	Use more descriptive plot titles.
icgmsplit	0	Split metacode into several files.
maxfld	10	Reserve memory for RIP.
ittrajcalc	0	Generate trajectory output files (use namelist *trajcalc* when this is set).
imakev5d	0	Generate output for Vis5D
ncarg_type	‘cgm’	Output type required. Options are ‘cgm’ *(default)*, ‘ps’, ‘pdf’, ‘pdfL’, ‘x11’. Where ‘pdf’ is portrait and ‘pdfL’ is landscape.
istopmiss	1	This switch determines the behavior for RIP when a user-requested field is not available. *The default is to stop*. Setting the switch to 0 tells RIP to ignore the missing field and to continue plotting.
rip_root	‘/dev/null’	Overwrite the environment variable RIP_ROOT.

Plot Specification Table

The second part of the RIP UIF consists of the Plot Specification Table. The PST provides all of the user control over particular aspects of individual frames and overlays.

The basic structure of the PST is as follows:

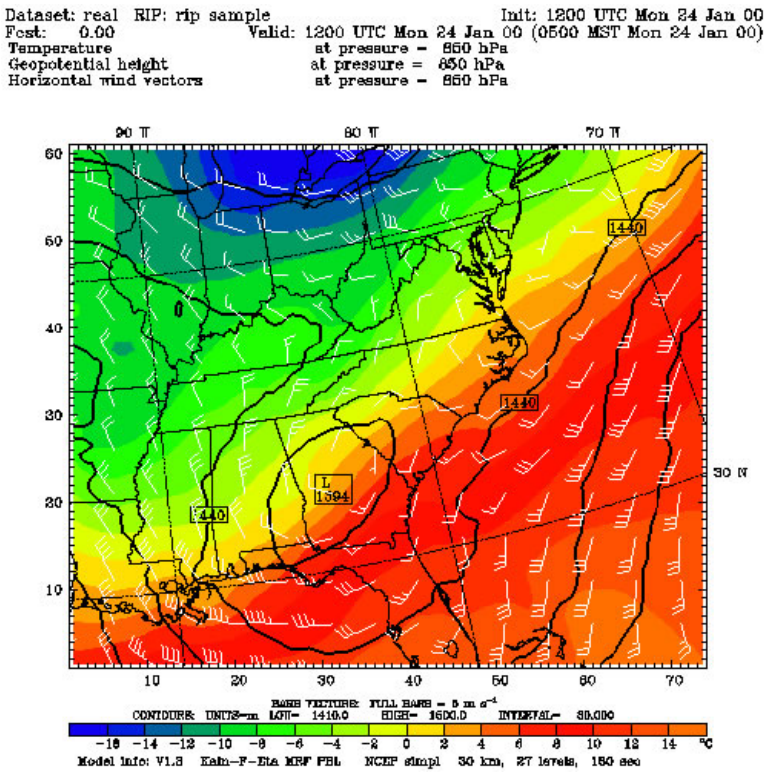
- The first line of the PST is a line of consecutive equal signs. This line as well as the next two lines is ignored by RIP, it is simply a banner that says this is the start of the PST section.
- After that there are several groups of one or more lines separated by a full line of equal signs. Each group of lines is a frame specification group (FSG), and it describes what will be plotted in a single frame of metacode. Each FSG must end with a full line of equal signs, so that RIP can determine where individual frames starts and ends.
- Each line within a FGS is referred to as a plot specification line (PSL). A FSG that consists of three PSL lines will result in a single metacode frame with three overlaid plots.

Example of a frame specification groups (FSG's):

```
 ================================================
  feld=tmc; ptyp=hc; vcor=p; levs=850; >
    cint=2; cmth=fill; cosq=-32,light.violet,-24,
    violet,-16,blue,-8,green,0,yellow,8,red,>
    16,orange,24,brown,32,light.gray
  feld=ght; ptyp=hc; cint=30; linw=2
  feld=uuu,vvv; ptyp=hv; vcmx=-1; colr=white; intv=5
  feld=map; ptyp=hb
  feld=tic; ptyp=hb
_================================================
```

This **FSG** will generate 5 frames to create a single plot (as shown below):

- Temperature in degrees C (*feld=**tmc***). This will be plotted as a horizontal contour plot (*ptyp=hc*), on pressure levels (*vcor=p*). The data will be interpolated to 850 hPa. The contour intervals are set to 2 (*cint=2*), and shaded plots (*cmth=fill*) will be generated with a color range from light violet to light gray.
- Geopotential heights (*feld=**ght***) will also be plotted as a horizontal contour plot. This time the contour intervals will be 30 (*cint=30*), and contour lines, with a line width of 2 (*linw=2*) will be used.
- Wind vectors (*feld=**uuu**,**vvv***), plotted as barbs (*vcmax=-1*).
- A map background will be displayed (*feld=**map***), and
- Tic marks will be placed on the plot (*feld=tic*).



Running RIP

Each execution of RIP requires three basic things: a RIP executable, a model data set and a user input file (UIF). The syntax for the executable, *rip*, is as follows:

`rip [-f] model-data-set-name rip-execution-name`

In the above, model-data-set-name is the same model-data-set-name that was used in creating the RIP data set with the program *ripdp*.

rip-execution-name is the unique name for this RIP execution, and it also defines the name of the UIF that RIP will look for.

The *–f* option causes the standard output *(i.e., the textual print out)* from RIP to be written to a file called *rip-execution-name.out*. Without the *–f* option, the standard output is sent to the screen.

e.g. `rip -f RIPDP/arw rip_sample`

If this is successful, the following files will be created:

rip_sample.*TYPE* - metacode file with requested plots
rip_sample.out - log file *(if –f used)* ; view this file if a problem occurred

The default output *TYPE* is ‘cgm’, metacode file. To view these, use the command ‘idt’.

e.g. `idt rip_sample.cgm`

For high quality images, create pdf or ps images directly **(ncarg_*type* = *pdf / ps*).**

See the **Tools** section in Chapter 10 of this User's Guide for more information concerning other types of graphical formats and conversions between graphical formats.

Examples of plots created for both idealized and real cases are available from:
http://www.mmm.ucar.edu/wrf/users/graphics/RIP4/RIP4.htm

ARWpost

The ARWpost package reads in WRF-ARW model data and creates output in either GrADS or Vis5D format. *Although conversion to Vis5D are currently still supported, more advance 3D visualization tools, like VAPOR and IDV, has been developed over the last couple of years and users are encouraged to explore those before starting new with Vis5D.*

The converter can read in WPS geogrid and metgrid data, and WRF-ARW input and output files.

The package makes use of the WRF IO API. The netCDF format has been tested extensively. GRIB1 format has been tested, but not as extensively. BINARY data cannot be read at the moment.

Necessary software

GrADS software - you can download and install GrADS from *http://grads/iges.org/grads*. The GrADS software is not needed to compile and run ARWpost.

Vis5D software (*http://www.ssec.wisc.edu/~billh/vis5d.html*)
Vis5D libraries must be installed to compile and run the ARWpost code, when creating Vis5D input data. If Vis5D files are not being created, these libraries are NOT needed to compile and run ARWpost.

Obtain the ARWpost TAR file from the WRF Download page (*http://www.mmm.ucar.edu/wrf/users/download/get_source.html*)
WRFV3 must be installed and available somewhere, as ARWpost makes use of the common IO API libraries from WRFV3.

Unzip and untar the ARWpost tar file.

The tar file contains the following directories and files:

- *README*, a text file containing basic information on running ARWpost.
- *arch/*, directory containing configure and compilation control.
- *clean*, a script to clean compiled code.
- *compile*, a script to compile the code.
- *configure*, a script to configure the compilation for your system.
- *namelist.ARWpost*, namelist to control the running of the code.
- *src/*, directory containing all source code.
- *scripts/*, directory containing some grads sample scripts.

- gribinfo.txt & gribmap.txt, files needed to process GRIB1 data. Do not edit these files.
- *util/*, a directory containing some utilities.

Environment Variables

Set the environment variable NETCDF to the location where your netCDF libraries are installed. Typically *(for cshrc shell):*

```
setenv NETCDF /usr/local/netcdf
```

Configure ARWpost

WRFV3 must be compiled and available on your system.

Type:

```
./configure
```

You will see a list of options for your computer *(below is an example for a Linux machine)*:

```
Will use NETCDF in dir: /usr/local/netcdf-pgi
------------------------------------------------------------
Please select from among the following supported platforms.
1. PC Linux i486 i586 i686, PGI compiler (no vis5d)
2. PC Linux i486 i586 i686, PGI compiler (vis5d)
3. PC Linux i486 i586 i686, Intel compiler (no vis5d)
4. PC Linux i486 i586 i686, Intel compiler (vis5d)

Enter selection [1-4]
```

Make sure the netCDF path is correct.
Pick compile options for your machine *(if you do not have Vis5D, or if you do not plan on using it, pick an option without Vis5D libraries).*

Compile ARWpost

If your **WRFV3** code is NOT compiled under **../WRFV3**, edit configure.arwp, and set **"WRF_DIR"** to the correct location of your WRFV3 code.

Type**:**

```
./compile
```

If successful, the executable `ARWpost.exe` will be created.

Edit the namelist.ARWpost file

Set input and output file names and fields to process (***&io***)

Variable	Value	Description
&datetime		
start_date; end_date		Start and end dates to process. Format: YYYY-MM-DD_HH:00:00
interval_seconds	0	Interval in seconds between data to process. If data is available every hour, and this is set to every 3 hours, the code will skip past data not required.
tacc	0	Time tolerance in seconds. Any time in the model output that is within *tacc* seconds of the time specified will be processed.
debug_level	0	Set higher to debugging is required.
&io		
io_form_input		2=netCDF, 5=GRIB1
input_root_name	./	Path and root name of files to use as input. All files starting with the root name will be processed. Wild characters are allowed.
output_root_name	./	Output root name. When converting data to GrADS, *output_root_name*.ctl and *output_root_name*.dat will be created. For Vis5D, *output_root_name*.v5d will be created.
output_title	Title as in WRF file	Use to overwrite title used in GrADS .ctl file.
mercator_defs	.False.	Set to true if mercator plots are distorted.
output_type	‘grads’	Options are ‘grads’ or ‘v5d’
split_output	.False.	Use if you want to split our GrADS output files into a number of smaller files *(a common .ctl file will be used for all .dat files).*
frames_per_outfile	1	If *split_output* is .True., how many time periods are required per output *(.dat)* file.

plot	'all'	Which fields to process. 'all' – all fields in WRF file 'list' – only fields as listed in the *'fields'* variable. 'all_list' – all fields in WRF file and all fields listed in the *'fields'* variable. Order has no effect, i.e., *'all_list'* and *'list_all'* are similar. If '*list*' is used, a list of variables must be supplied under '*fields*'. Use *'list'* to calculate diagnostics.
fields		Fields to plot. Only used if '*list'* was used in the '*plot*' variable.
&interp		
interp_method	0	0 - sigma levels, -1 - code defined "nice" height levels, 1 - user defined height or pressure levels
interp_levels		Only used if interp_method=1 Supply levels to interpolate to, in hPa (pressure) or km (height). Supply levels bottom to top.
extrapolate	.false.	Extrapolate the data below the ground if interpolating to either pressure or height.

Available diagnostics:

cape - 3d cape
cin - 3d cin
mcape - maximum cape
mcin - maximum cin
clfr - low/middle and high cloud fraction
dbz - 3d reflectivity
max_dbz - maximum reflectivity
geopt - geopotential
height - model height in km
lcl - lifting condensation level
lfc - level of free convection
pressure - full model pressure in hPa
rh - relative humidity
rh2 - 2m relative humidity
theta - potential temperature
tc - temperature in degrees C
tk - temperature in degrees K
td - dew point temperature in degrees C
td2 - 2m dew point temperature in degrees C

slp - sea level pressure
umet and **vmet** - winds rotated to earth coordinates
u10m and **v10m** - 10m winds rotated to earth coordinates
wdir - wind direction
wspd - wind speed coordinates
wd10 - 10m wind direction
ws10 - 10m wind speed

Run ARWpost

Type:

```
./ARWpost.exe
```

This will create *output_root_name*.**dat** and *output_root_name*.**ctl** files if creating GrADS input, and *output_root_name*.**v5d**, if creating Vis5D input.

NOW YOU ARE READY TO VIEW THE OUTPUT

GrADS

For general information about working with GrADS, view the GrADS home page: *http://grads.iges.org/grads/*

To help users get started a number of GrADS scripts have been provided:

- The scripts are all available in the scripts/ directory.
- The scripts provided are only examples of the type of plots one can generate with GrADS data.
- The user will need to modify these scripts to suit their data (e.g., if you did not specify 0.25 km and 2 km as levels to interpolate to when you run the "bwave" data through the converter, the "bwave.gs" script will not display any plots, since it will specifically look for these to levels).
- Scripts must be copied to the location of the input data.

GENERAL SCRIPTS

cbar.gs	Plot color bar on shaded plots (from GrADS home page)
rgbset.gs	Some extra colors *(Users can add/change colors from color number 20 to 99)*

skew.gs Program to plot a skewT

TO RUN TYPE: run skew.gs (needs pressure level TC,TD,U,V as input)
User will be prompted if a hardcopy of the plot must be create - 1 for yes and 0 for no.
If 1 is entered, a GIF image will be created.
Need to enter lon/lat of point you are interested in
Need to enter time you are interested in
Can overlay 2 different times

plot_all.gs Once you have opened a GrADS window, all one needs to do is run this script.
It will automatically find all .ctl files in the current directory and list them so one can pick which file to open.
Then the script will loop through all available fields and plot the ones a user requests.

SCRIPTS FOR REAL DATA

real_surf.gs Plot some surface data
Need input data on model levels

plevels.gs Plot some pressure level fields
Need model output on pressure levels

rain.gs Plot total rainfall
Need a model output data set (any vertical coordinate), that contain fields "RAINC" and "RAINNC"

cross_z.gs Need z level data as input
Will plot a NS and EW cross section of RH and T (C)
Plots will run through middle of the domain

zlevels.gs Plot some height level fields
Need input data on height levels
Will plot data on 2, 5, 10 and 16km levels

input.gs Need WRF INPUT data on height levels

SCRIPTS FOR IDEALIZED DATA

bwave.gs Need height level data as input
Will look for 0.25 and 2 km data to plot

grav2d.gs Need normal model level data

hill2d.gs Need normal model level data

qss.gs Need height level data as input.
Will look for heights 0.75, 1.5, 4 and 8 km to plot

sqx.gs Need normal model level data a input

sqy.gs Need normal model level data a input

Examples of plots created for both idealized and real cases are available from: *http://www.mmm.ucar.edu/wrf/users/graphics/ARWpost/ARWpost.htm*

Trouble Shooting

*The code executes correctly, but you get "**NaN**" or "**Undefined Grid**" for all fields when displaying the data.*

Look in the .ctl file.

a) If the second line is:

> **options byteswapped**
>
> Remove this line from your .ctl file and try to display the data again.
> If this SOLVES the problem, you need to remove the **-Dbytesw** option from configure.arwp

b) If the line below does NOT appear in your .ctl file:

> **options byteswapped**
>
> ADD this line as the second line in the .ctl file.
> Try to display the data again.
> If this SOLVES the problem, you need to ADD the **-Dbytesw** option for configure.arwp

The line "options byteswapped" is often needed on some computers (DEC alpha as an example). It is also often needed if you run the converter on one computer and use another to display the data.

Vis5D

For general information about working with Vis5D, view the Vis5D home page: *http://www.ssec.wisc.edu/~billh/vis5d.html*

WPP

The NCEP WRF Postprocessor was designed to interpolate both WRF-NMM and WRF-ARW output from their native grids to National Weather Service (NWS) standard levels (pressure, height, etc.) and standard output grids (AWIPS, Lambert Conformal, polar-stereographic, etc.) in NWS and World Meteorological Organization (WMO) GRIB format. This package also provides an option to output fields on the model's native vertical levels.

The adaptation of the original WRF Postprocessor package and User's Guide (by Mike Baldwin of NSSL/CIMMS and Hui-Ya Chuang of NCEP/EMC) was done by Lígia Bernardet (NOAA/ESRL/DTC) in collaboration with Dusan Jovic (NCEP/EMC), Robert Rozumalski (COMET), Wesley Ebisuzaki (NWS/HQTR), and Louisa Nance (NCAR/DTC). Upgrades to WRF Postprocessor versions 2.2 and higher were performed by Hui-Ya Chuang and Dusan Jovic (NCEP/EMC).

This document will mainly deal with running the WPP package for the WRF-ARW modeling system. For details on running the package for the WRF-NMM system, please refer to the WRF-NMM User's Guide *(http://www.dtcenter.org/wrf-nmm/users/docs/user_guide/V3/index.htm)*.

Necessary software

The WRF Postprocessor requires the same Fortran and C compilers used to build the WRF model. In addition to the netCDF library, the WRF I/O API libraries, which are included in the WRF model tar file, are also required.

The WRF Postprocessor has some visualization scripts included to create graphics using either GrADS (*http://grads.iges.org/home.html*) or GEMPAK (*http://my.unidata.ucar.edu/content/software/gempak/index.html*). These packages are not part of the WPP installation and would need to be installed.

The WRF Postprocessor package can be downloaded from: http://www.dtcenter.org/wrf-nmm/users/downloads/

Note: Always obtain the latest version of the code if you are not trying to continue a pre-existing project. WPPV3 is just used as an example here.

Once the ***tar*** file is obtained, ***gunzip*** and ***untar*** the file.

```
tar -xvf WPPV3.tar.gz
```

This command will create a directory called ***WPPV3***. Under the main directory, there are five subdirectories:

- *sorc/*, contains source codes for ***wrfpost***, ***ndate***, and ***copygb***.
- *scripts*/, contains sample running scripts
  run_wrfpost: run ***wrfpost*** and ***copygb***.
  run_wrfpostandgempak: run ***wrfpost***, ***copygb***, and GEMPAK to plot various fields.
  run_wrfpostandgrads: run ***wrfpost***, ***copygb***, and GrADS to plot various fields.
  run_wrfpost_frames: run ***wrfpost*** and ***copygb*** on a single wrfout file containing multiple forecast times.
  run_wrfpost_gracet: run ***wrfpost*** and ***copygb*** on ***wrfout*** files with non-zero minutes/seconds.
  run_wrfpost_minute: run ***wrfpost*** and ***copygb*** for sub-hourly ***wrfout*** files.
- *lib/*, contains source code subdirectories for the WRF Postprocessor libraries and is the directory where the WRF Postprocessor compiled libraries will reside.
  w3lib: Library for coding and decoding data in GRIB format. *(**Note**: The version of this library included in this package is Endian independent and can be used on LINUX and IBM systems.)*
  iplib: General interpolation library (see ***lib/iplib/iplib.doc***)
  splib: Spectral transform library (see ***lib/splib/splib.doc***)
  wrfmpi_stubs: Contains some ***C*** and ***FORTRAN*** codes to generate the ***libmpi.a*** library. It supports MPI implementation for LINUX applications.
- *parm/*, contains the parameter files, which can be modified by the user to control how the post processing is performed.
- *exec/*, location of executables after compilation.

Building the WPP Code

WPP uses a build mechanism similar to that used by the WRF model. First issue the ***configure*** command, followed by the ***compile*** command.

If the WRFV3 directory is not located at:

../WRFV3

the following environment variable must be set:

setenv WRF_DIR */home/user/WRFV3*

If this is not set, the configure script will prompt you for it.

Type ***configure***, and provide the required info. For example:

./configure

You will be given a list of choices for your computer.

Choices for IBM machines are as follows:
1. AIX xlf compiler with xlc (serial)

Choices for LINUX operating systems are as follows:
1. LINUX i486 i586 i686, PGI compiler (serial)
2. LINUX i486 i586 i686, Intel compiler (serial)
3. LINUX i486 i586 i686, gfortran compiler (serial)

Choose one of the configure options listed. Check the ***configure.wpp*** file created and edit for compile options/paths, if necessary.

To compile WPP, enter the following command:

./compile >& compile_wpp.log &

This command should create four WRF Postprocessor libraries in ***lib/*** (***libmpi.a***, ***libsp.a***, ***libip.a***, and ***libw3.a***) and three WRF Postprocessor executables in ***exec/*** (***wrfpost.exe***, ***ndate.exe***, and ***copygb.exe***).

To remove all built files, as well as the ***configure.wpp***, type:

clean

This action is recommended if a mistake is made during the installation process

WPP Functionalities

The WRF Postprocessor V3,
- is compatible with WRF version 2.2 and higher.
- can be used to post-process both WRF-ARW and WRF-NMM forecasts.
- can ingest WRF history files (***wrfout****) in two formats: netCDF and binary.

The WRF Postprocessor is divided into two parts, ***wrfpost*** and ***copygb***:

wrfpost
- Interpolates the forecasts from the model's native vertical coordinate to NWS standard output levels (e.g., *pressure, height*) and computes mean sea level pressure. If the requested field is on a model's native level, then no vertical interpolation is performed.

- Computes diagnostic output quantities (e.g., *convective available potential energy, helicity, radar reflectivity*). A list of fields that can be generated by ***wrfpost*** is shown in *Table 2*.
- Outputs the results in NWS and WMO standard GRIB1 format (for GRIB documentation, see *http://www.nco.ncep.noaa.gov/pmb/docs/*).
- De-staggers the WRF-ARW forecasts from a C-grid to an A-grid.
- Outputs two navigation files, **copygb_nav.txt** and **copygb_hwrf.txt** (these are ONLY used for WRF-NMM).

copygb

- Since *wrfpost* de-staggers WRF-ARW from a C-grid to an A-grid, WRF-ARW data can be displayed directly without going through *copygb.*
- No de-staggering is applied when posting WRF-NMM forecasts. Therefore, the posted WRF-NMM output is still on the staggered native E-grid and must go through *copygb* to be interpolated to a regular non-staggered grid.
- copygb is mainly used by WRF-NMM - see the WRF-NMM User's Guide (*http://www.dtcenter.org/wrf-nmm/users/docs/user_guide/WPS/index.php*).

An additional utility called ***ndate*** is distributed with the WRF Postprocessor tar-file. This utility is used to format the dates of the forecasts to be posted for ingestion by the codes.

Computational Aspects and Supported Platforms

The WRF Postprocessor v3.0 has been tested on IBM and LINUX platforms. Only ***wrfpost*** (step 1) is parallelized because it requires several 3-dimensional arrays (the model's history variables) for the computations. When running ***wrfpost*** on more than one processor, the last processor will be designated as an I/O node, while the rest of the processors are designated as computational nodes. For example, if three processors are requested to run the ***wrfpost***, only the first two processors will be used for computation, while the third processor will be used to write output to GRIB files.

Setting up the WRF model to interface with the WRF Postprocessor

The ***wrfpost*** program is currently set up to read a large number of fields from the WRF model history files. This configuration stems from NCEP's need to generate all of its required operational products. A list of the fields that are currently read in by ***wrfpost*** is provided in Table 1. This program is configured such that is will run successfully if an expected input field is missing from the WRF history file as long as this field is not required to produce a requested output field. If the pre-requisites for a requested output field are missing from the WRF history file, ***wrfpost*** will abort at run time.

Take care not to remove fields from the ***wrfout*** files, which may be needed for diagnostic purposes by the WPP package. For example, if isobaric state fields are requested, but the

pressure fields on model interfaces (P and PB) are not available in the history file, ***wrfpost*** will abort at run time. In general, the default fields available in the ***wrfout*** files are sufficient to run WPP. The fields written to the WRF history file are controlled by the settings in the Registry file (see ***Registry.EM)*** in the ***Registry*** subdirectory of the main ***WRFV3*** directory).

Table 1: *List of all possible fields read in by* ***wrfpost*** *for the WRF-ARW:*

T	MUB	SFROFF
U	P_TOP	UDROFF
V	PHB	SFCEVP
QVAPOR	PH	SFCEXC
QCLOUD	SMOIS	VEGFRA
QICE	TSLB	ACSNOW
QRAIN	CLDFRA	ACSNOM
QSNOW	U10	CANWAT
QGRAUP	V10	SST
W	TH2	THZ0
PB	Q2	QZ0
P	SMSTAV	UZ0
MU	SMSTOT	VZ0
QSFC	HGT	ISLTYP
Z0	ALBEDO	ISLOPE
UST	GSW	XLAND
AKHS	GLW	XLAT
AKMS	TMN	XLONG
TSK	HFX	MAPFAC_M
RAINC	LH	STEPBL
RAINNC	GRDFLX	HTOP
RAINCV	SNOW	HBOT
RAINNCV	SNOWC	

Note: For WRF-ARW, the accumulated precipitation fields (***RAINC*** and ***RAINNC***) are run total accumulations.

Control File Overview

The user interacts with ***wrfpost*** through the control file, ***parm/wrf_cntrl.parm***. The control file is composed of a header and a body. The header specifies the output file information. The body allows the user to select which fields and levels to process.

The header of the ***wrf_cntrl.parm*** file contains the following variables:

- **KGTYPE**: defines output grid type, which should always be 255.
- **IMDLTY:** identifies the process ID for AWIPS.
- **DATSET**: defines the prefix used for the output file name. Currently set to "***WRFPRS"***.

The body of the ***wrf_cntrl.parm*** file is composed of a series of line pairs, for example:

```
(PRESS ON MDL SFCS  ) SCAL=( 3.0)
L=(11000 00000 00000 00000 00000 00000 00000 00000 00000 00000 00000 00000 00000 00000)
```

where,

- The top line specifies the variable (e.g. PRESS) to process, the level type (e.g. ON MDL SFCS) a user is interested in, and the degree of accuracy to be retained (SCAL=3.0) in the GRIB output.

  SCAL defines the precision of the data written out to the GRIB format. Positive values denote decimal scaling (maintain that number of significant digits), while negative values describe binary scaling (precise to 2^{SCAL}; i.e., SCAL=-3.0 gives output precise to the nearest 1/8).

  A list of all possible output fields for ***wrfpost*** is provided in Table 2. This table provides the full name of the variable in the first column and an abbreviated name in the second column. The abbreviated names are used in the control file. Note that the variable names also contain the type of level on which they are output. For instance, temperature is available on “model surface” and “pressure surface”.
- The second line specifies the levels on which the variable is to be posted.

Controlling which fields *wrfpost* outputs

To output a field, the body of the control file needs to contain an entry for the appropriate variable and output for this variable must be turned on for at least one level (see "*Controlling which levels wrfpost outputs"*). If an entry for a particular field is not yet available in the control file, two lines may be added to the control file with the appropriate entries for that field.

Controlling which levels *wrfpost* outputs

The second line of each pair determines which levels ***wrfpost*** will output. Output on a given level is turned off by a “0” or turned on by a “1”.

- For isobaric output, 47 levels are possible, from 2 to 1013 hPa *(8 levels above 75 mb and then every 25 mb from 75 to 1000mb)*. The complete list of levels is specified in *sorc/wrfpost/POSTDATA.f*

  Modify specification of variable LSM in the file CTLBLK.comm to change the number of pressure levels: PARAMETER (LSM=47)
  Modify specification of SPL array in the subroutine ***POSTDATA.f*** to change the values of pressure levels:
  DATA SPL/200.,500.,700.,1000.,2000.,3000.
  &,5000.,7000.,7500.,10000.,12500.,15000.,17500.,20000., …
- For model-level output, all model levels are possible, from the highest to the lowest.

- When using the Noah LSM the *soil layers* are 0-10 cm, 10-40 cm, 40-100 cm, and 100-200 cm.
- When using the RUC LSM the *soil levels* are 0 cm, 5 cm, 20 cm, 40 cm, 160 cm and 300 cm. For the RUC LSM it is also necessary to turn on two additional output levels in the ***wrf_cntrl.parm*** to output 6 levels rather than the default 4 layers for the Noah LSM.
- For PBL layer averages, the levels correspond to 6 layers with a thickness of 30 hPa each.
- For flight level, the levels are 914 m, 1524 m, 1829 m, 2134 m, 2743 m, 3658 m, and 6000 m.
- For AGL RADAR Reflectivity, the levels are 4000 and 1000 m.
- For surface or shelter-level output, only the first position of the line can be turned on.

  For example, the sample control file ***parm/wrf_cntrl.parm*** has the following entry for surface dew point temperature:

  (SURFACE DEWPOINT) SCAL=(4.0)
  L=(00000 00000 00000 00000 00000 00000 00000 00000 00000 00000 00000 00000 00000 00000 00000)

  Based on this entry, surface dew point temperature will not be output by ***wrfpost***. To add this field to the output, modify the entry to read:

  (SURFACE DEWPOINT) SCAL=(4.0)
  L=(10000 00000 00000 00000 00000 00000 00000 00000 00000 00000 00000 00000 00000 00000 00000)

Running WPP

Number of scripts for running the WRF Postprocessor package is included in the tar file:

run_wrfpost
run_wrfpostandgrads
run_wrfpostandgempak
run_wrfpost_frames
run_wrfpost_gracet
run_wrfpost_minute

Before running any of the above listed scripts, perform the following instructions:

1. *cd* to your *DOMAINPATH* directory.

2. Make the following directories. The first will hold the WRF Postprocessor results. The second is where you will place your copy of the *wrf_cntrl.parm* file.

```
mkdir postprd
mkdir  parm
```

3. Copy the default *WPPV3/parm/wrf_cntrl.parm* to your working. Edit the *wrf_cntrl.parm* file to reflect the fields and levels you want *wrfpost* to output.

4. Copy the script *(WPPV3/scripts/run_wrfpost*)* of your choice to the *postprd*/.

5. Edit the run script as outlined below.

Once these directories are set up and the edits outlined above are completed, the scripts can be run interactively from the *postprd* directory by simply typing the script name on the command line.

Overview of the WPP run scripts

Note: It is recommended that the user refer to the script while reading this overview.

1. Set up environmental variables:

   TOP_DIR: top level directory for source codes (*WPPV3* and *WRFV3*)
   DOMAINPATH: top level directory of WRF model run

   Note: The scripts are configured such that *wrfpost* expects the WRF history files (*wrfout** files) to be in subdirectory *wrfprd*, the *wrf_cntrl.parm* file to be in the subdirectory *parm* and the postprocessor working directory to be a subdirectory called *postprd* under *DOMAINPATH*.

2. Specify dynamic core being run ("*ARW*" for the WRF-ARW model)

3. Specify the forecast cycles to be post-processed:
   startdate: YYYYMMDDHH of forecast cycle
   fhr: first forecast hour
   lastfhr: last forecast hour
   incrementhr: increment (in hours) between forecast files

4. Define the location of the post-processor executables.

5. Link the microphysical table *${WRFPATH}/run/ETAMP_DATA* and the control file *../parm/wrf_control.parm* to the working directory.

6. Set up how many domains will be post-processed:
   For runs with a single domain, use "for domain d01".
   For runs with multiple domains, use "for domain d01 d02 .. d*nn*"

7. Create namelist *itag* that will be read in by *wrfpost.exe* from stdin *(unit 5).* This namelist contains 4 lines:
   i. Name of the WRF output file to be posted.
   ii. Format of WRF model output (netCDF or binary).
   iii. Forecast valid time (not model start time) in WRF format.
   iv. Model name (ARW for the WRF_ARW model).

8. Run *wrfpost* and check for errors. The execution command in the distributed scripts is for a single processor *wrfpost.exe* < *itag* > *outpost*. To run *wrfpost* on multiple processors, the command line should be:

   mpirun -np N wrfpost.exe < *itag* > *outpost* (for LINUX-MPI systems)
   mpirun.lsf wrfpost.exe < *itag* > *outpost* (for IBM)

If scripts *run_wrfpostandgrads* or *run_wrfpostandgempak* are used, additional steps are taken to create image files (see **Visualization** section below).

Upon a successful run, *wrfpost* will generate the output file ***WRFPRS_dnn.hh*** *(linked to wrfpr_dnn.hh)*, in the post-processor working directory, where *"nn"* is the domain ID and *"hh"* the forecast hour. In addition, the script *run_wrfpostandgrads* will produce a suite of gif images named *variablehh_dnn_GrADS.gif*, and the script *run_wrfpostandgempak* will produce a suite of gif images named *variable_dnn_hh.gif*.

If the run did not complete successfully, a log file in the post-processor working directory called *wrfpost_dnn.hh.out*, where "*nn*" is the domain ID and "*hh*" is the forecast hour, may be consulted for further information.

Visualization

GEMPAK

The GEMPAK utility *nagrib* is able to decode GRIB files whose navigation is on any non-staggered grid. Hence, GEMPAK is able to decode GRIB files generated by the WRF Postprocessing package and plot horizontal fields or vertical cross sections.

A sample script named *run_wrfpostandgempak*, which is included in the *scripts* directory of the tar file, can be used to run *wrfpost* and plot the following fields using GEMPAK:

- ***Sfcmap_dnn_hh.gif:*** mean SLP and 6 hourly precipitation
- ***PrecipType_dnn_hh.gif:*** precipitation type (just snow and rain)
- ***850mbRH_dnn_hh.gif:*** 850 mb relative humidity
- ***850mbTempandWind_dnn_hh.gif:*** 850 mb temperature and wind vectors
- ***500mbHandVort_dnn_hh.gif:*** 500 mb geopotential height and vorticity

- ***250mbWindandH_dnn_hh.gif:*** 250 mb wind speed isotacs and geopotential height

This script can be modified to customize fields for output. GEMPAK has an online users guide at *http://www.unidata.ucar.edu/software/gempak/help_and_documentation/manual/*.

In order to use the script *run_wrfpostandgempak*, it is necessary to set the environment variable ***GEMEXEC*** to the path of the GEMPAK executables. For example,

```
setenv GEMEXEC /usr/local/gempak/bin
```

GrADS

The GrADS utilities *grib2ctl.pl* and *gribmap* are able to decode GRIB files whose navigation is on any non-staggered grid. These utilities and instructions on how to use them to generate GrADS control files are available from: http://www.cpc.ncep.noaa.gov/products/wesley/grib2ctl.html.

The GrADS package is available from: http://grads.iges.org/grads/grads.html.
GrADS has an online Users' Guide at: http://grads.iges.org/grads/gadoc/.
A list of basic commands for GrADS can be found at:
http://grads.iges.org/grads/gadoc/reference_card.pdf.

A sample script named *run_wrfpostandgrads*, which is included in the *scripts* directory of the WRF Postprocessing package, can be used to run *wrfpost* and plot the following fields using GrADS:

- ***Sfcmaphh_dnn_GRADS.gif***: mean SLP and 6-hour accumulated precipitation.
- ***850mbRHhh_dnn_GRADS.gif***: 850 mb relative humidity
- ***850mbTempandWindhh_dnn_GRADS.gif***: 850 mb temperature and wind vectors
- ***500mbHandVorthh_dnn_GRADS.gif***: 500 mb geopotential heights and absolute vorticity
- ***250mbWindandHhh_dnn_GRADS.gif***: 250 mb wind speed isotacs and geopotential heights

In order to use the script *run_wrfpostandgrads*, it is necessary to:

1. Set the environmental variable *GADDIR* to the path of the GrADS fonts and auxiliary files. For example,

```
setenv GADDIR /usr/local/grads/data
```

2. Add the location of the GrADS executables to the *PATH*. For example,

```
setenv PATH /usr/local/grads/bin:$PATH
```

3. Link script *cbar.gs* to the post-processor working directory. *(This script is provided in WPP package, and the run_wrfpostandgrads script makes a link from scripts/ to postprd/.)* To generate the above plots, GrADS script *cbar.gs* is invoked. This script can also be obtained from the GrADS library of scripts at: *http://grads.iges.org/grads/gadoc/library.html*

Fields produced by *wrfpost*

Table 2 lists basic and derived fields that are currently produced by *wrfpost*. The abbreviated names listed in the second column describe how the fields should be entered in the control file (*wrf_cntrl.parm*).

Table 2: *Fields produced by **wrfpost** (column 1), abbreviated names used in the **wrf_cntrl.parm** file (column 2), corresponding GRIB identification number for the field (column 3), and corresponding GRIB identification number for the vertical coordinate (column 4).*

Field name	Name in control file	Grib ID	Vertical level
Radar reflectivity on model surface	RADAR REFL MDL SFCS	211	109
Pressure on model surface	PRESS ON MDL SFCS	1	109
Height on model surface	HEIGHT ON MDL SFCS	7	109
Temperature on model surface	TEMP ON MDL SFCS	11	109
Potential temperature on model surface	POT TEMP ON MDL SFCS	13	109
Dew point temperature on model surface	DWPT TEMP ON MDL SFC	17	109
Specific humidity on model surface	SPEC HUM ON MDL SFCS	51	109
Relative humidity on model surface	REL HUM ON MDL SFCS	52	109
Moisture convergence on model surface	MST CNVG ON MDL SFCS	135	109
U component wind on model surface	U WIND ON MDL SFCS	33	109
V component wind on model surface	V WIND ON MDL SFCS	34	109
Cloud water on model surface	CLD WTR ON MDL SFCS	153	109
Cloud ice on model surface	CLD ICE ON MDL SFCS	58	109
Rain on model surface	RAIN ON MDL SFCS	170	109
Snow on model surface	SNOW ON MDL SFCS	171	109
Cloud fraction on model surface	CLD FRAC ON MDL SFCS	71	109
Omega on model surface	OMEGA ON MDL SFCS	39	109
Absolute vorticity on model surface	ABS VORT ON MDL SFCS	41	109
Geostrophic streamfunction on model surface	STRMFUNC ON MDL SFCS	35	109
Turbulent kinetic energy on model surface	TRBLNT KE ON MDL SFC	158	109
Richardson number on model surface	RCHDSN NO ON MDL SFC	254	109
Master length scale on model surface	MASTER LENGTH SCALE	226	109
Asymptotic length scale on model surface	ASYMPT MSTR LEN SCL	227	109
Radar reflectivity on pressure surface	RADAR REFL ON P SFCS	211	100
Height on pressure surface	HEIGHT OF PRESS SFCS	7	100
Temperature on pressure surface	TEMP ON PRESS SFCS	11	100
Potential temperature on pressure surface	POT TEMP ON P SFCS	13	100

Dew point temperature on pressure surface	DWPT TEMP ON P SFCS	17	100
Specific humidity on pressure surface	SPEC HUM ON P SFCS	51	100
Relative humidity on pressure surface	REL HUMID ON P SFCS	52	100
Moisture convergence on pressure surface	MST CNVG ON P SFCS	135	100
U component wind on pressure surface	U WIND ON PRESS SFCS	33	100
V component wind on pressure surface	V WIND ON PRESS SFCS	34	100
Omega on pressure surface	OMEGA ON PRESS SFCS	39	100
Absolute vorticity on pressure surface	ABS VORT ON P SFCS	41	100
Geostrophic streamfunction on pressure surface	STRMFUNC ON P SFCS	35	100
Turbulent kinetic energy on pressure surface	TRBLNT KE ON P SFCS	158	100
Cloud water on pressure surface	CLOUD WATR ON P SFCS	153	100
Cloud ice on pressure surface	CLOUD ICE ON P SFCS	58	100
Rain on pressure surface	RAIN ON P SFCS	170	100
Snow water on pressure surface	SNOW ON P SFCS	171	100
Total condensate on pressure surface	CONDENSATE ON P SFCS	135	100
Mesinger (Membrane) sea level pressure	MESINGER MEAN SLP	130	102
Shuell sea level pressure	SHUELL MEAN SLP	2	102
2 M pressure	SHELTER PRESSURE	1	105
2 M temperature	SHELTER TEMPERATURE	11	105
2 M specific humidity	SHELTER SPEC HUMID	51	105
2 M dew point temperature	SHELTER DEWPOINT	17	105
2 M RH	SHELTER REL HUMID	52	105
2 M mixing ratio	SHELTER MIX RATIO	53	105
10 M u component wind	U WIND AT ANEMOM HT	33	105
10 M v component wind	V WIND AT ANEMOM HT	34	105
10 M potential temperature	POT TEMP AT 10 M	13	105
10 M specific humidity	SPEC HUM AT 10 M	51	105
Surface pressure	SURFACE PRESSURE	1	1
Terrain height	SURFACE HEIGHT	7	1
Skin potential temperature	SURFACE POT TEMP	13	1
Skin specific humidity	SURFACE SPEC HUMID	51	1
Skin dew point temperature	SURFACE DEWPOINT	17	1
Skin Relative humidity	SURFACE REL HUMID	52	1
Skin temperature	SFC (SKIN) TEMPRATUR	11	1
Soil temperature at the bottom of soil layers	BOTTOM SOIL TEMP	85	111
Soil temperature in between each of soil layers	SOIL TEMPERATURE	85	112
Soil moisture in between each of soil layers	SOIL MOISTURE	144	112
Snow water equivalent	SNOW WATER EQUIVALNT	65	1
Snow cover in percentage	PERCENT SNOW COVER	238	1
Heat exchange coeff at surface	SFC EXCHANGE COEF	208	1
Vegetation cover	GREEN VEG COVER	87	1
Soil moisture availability	SOIL MOISTURE AVAIL	207	112
Ground heat flux - instantaneous	INST GROUND HEAT FLX	155	1
Lifted index—surface based	LIFTED INDEX—SURFCE	131	101
Lifted index—best	LIFTED INDEX—BEST	132	116
Lifted index—from boundary layer	LIFTED INDEX—BNDLYR	24	116
CAPE	CNVCT AVBL POT ENRGY	157	1
CIN	CNVCT INHIBITION	156	1
Column integrated precipitable water	PRECIPITABLE WATER	54	200
Column integrated cloud water	TOTAL COLUMN CLD WTR	136	200
Column integrated cloud ice	TOTAL COLUMN CLD ICE	137	200

Column integrated rain	TOTAL COLUMN RAIN	138	200
Column integrated snow	TOTAL COLUMN SNOW	139	200
Column integrated total condensate	TOTAL COL CONDENSATE	140	200
Helicity	STORM REL HELICITY	190	106
U component storm motion	U COMP STORM MOTION	196	106
V component storm motion	V COMP STORM MOTION	197	106
Accumulated total precipitation	ACM TOTAL PRECIP	61	1
Accumulated convective precipitation	ACM CONVCTIVE PRECIP	63	1
Accumulated grid-scale precipitation	ACM GRD SCALE PRECIP	62	1
Accumulated snowfall	ACM SNOWFALL	65	1
Accumulated total snow melt	ACM SNOW TOTAL MELT	99	1
Precipitation type (4 types) - instantaneous	INSTANT PRECIP TYPE	140	1
Precipitation rate - instantaneous	INSTANT PRECIP RATE	59	1
Composite radar reflectivity	COMPOSITE RADAR REFL	212	200
Low level cloud fraction	LOW CLOUD FRACTION	73	214
Mid level cloud fraction	MID CLOUD FRACTION	74	224
High level cloud fraction	HIGH CLOUD FRACTION	75	234
Total cloud fraction	TOTAL CLD FRACTION	71	200
Time-averaged total cloud fraction	AVG TOTAL CLD FRAC	71	200
Time-averaged stratospheric cloud fraction	AVG STRAT CLD FRAC	213	200
Time-averaged convective cloud fraction	AVG CNVCT CLD FRAC	72	200
Cloud bottom pressure	CLOUD BOT PRESSURE	1	2
Cloud top pressure	CLOUD TOP PRESSURE	1	3
Cloud bottom height (above MSL)	CLOUD BOTTOM HEIGHT	7	2
Cloud top height (above MSL)	CLOUD TOP HEIGHT	7	3
Convective cloud bottom pressure	CONV CLOUD BOT PRESS	1	242
Convective cloud top pressure	CONV CLOUD TOP PRESS	1	243
Shallow convective cloud bottom pressure	SHAL CU CLD BOT PRES	1	248
Shallow convective cloud top pressure	SHAL CU CLD TOP PRES	1	249
Deep convective cloud bottom pressure	DEEP CU CLD BOT PRES	1	251
Deep convective cloud top pressure	DEEP CU CLD TOP PRES	1	252
Grid scale cloud bottom pressure	GRID CLOUD BOT PRESS	1	206
Grid scale cloud top pressure	GRID CLOUD TOP PRESS	1	207
Convective cloud fraction	CONV CLOUD FRACTION	72	200
Convective cloud efficiency	CU CLOUD EFFICIENCY	134	200
Above-ground height of LCL	LCL AGL HEIGHT	7	5
Pressure of LCL	LCL PRESSURE	1	5
Cloud top temperature	CLOUD TOP TEMPS	11	3
Temperature tendency from radiative fluxes	RADFLX CNVG TMP TNDY	216	109
Temperature tendency from shortwave radiative flux	SW RAD TEMP TNDY	250	109
Temperature tendency from longwave radiative flux	LW RAD TEMP TNDY	251	109
Outgoing surface shortwave radiation - instantaneous	INSTN OUT SFC SW RAD	211	1
Outgoing surface longwave radiation - instantaneous	INSTN OUT SFC LW RAD	212	1
Incoming surface shortwave radiation - time-averaged	AVE INCMG SFC SW RAD	204	1
Incoming surface longwave radiation - time-averaged	AVE INCMG SFC LW RAD	205	1
Outgoing surface shortwave radiation - time-averaged	AVE OUTGO SFC SW RAD	211	1
Outgoing surface longwave radiation - time-averaged	AVE OUTGO SFC LW RAD	212	1
Outgoing model top shortwave radiation - time-averaged	AVE OUTGO TOA SW RAD	211	8
Outgoing model top longwave radiation - time-averaged	AVE OUTGO TOA LW RAD	212	8
Incoming surface shortwave radiation - instantaneous	INSTN INC SFC SW RAD	204	1
Incoming surface longwave radiation - instantaneous	INSTN INC SFC LW RAD	205	1
Roughness length	ROUGHNESS LENGTH	83	1
Friction velocity	FRICTION VELOCITY	253	1

Surface drag coefficient	SFC DRAG COEFFICIENT	252	1
Surface u wind stress	SFC U WIND STRESS	124	1
Surface v wind stress	SFC V WIND STRESS	125	1
Surface sensible heat flux - time-averaged	AVE SFC SENHEAT FX	122	1
Ground heat flux - time-averaged	AVE GROUND HEAT FX	155	1
Surface latent heat flux - time-averaged	AVE SFC LATHEAT FX	121	1
Surface momentum flux - time-averaged	AVE SFC MOMENTUM FX	172	1
Accumulated surface evaporation	ACC SFC EVAPORATION	57	1
Surface sensible heat flux - instantaneous	INST SFC SENHEAT FX	122	1
Surface latent heat flux - instantaneous	INST SFC LATHEAT FX	121	1
Latitude	LATITUDE	176	1
Longitude	LONGITUDE	177	1
Land sea mask (land=1, sea=0)	LAND SEA MASK	81	1
Sea ice mask	SEA ICE MASK	91	1
Surface midday albedo	SFC MIDDAY ALBEDO	84	1
Sea surface temperature	SEA SFC TEMPERATURE	80	1
Press at tropopause	PRESS AT TROPOPAUSE	1	7
Temperature at tropopause	TEMP AT TROPOPAUSE	11	7
Potential temperature at tropopause	POTENTL TEMP AT TROP	13	7
U wind at tropopause	U WIND AT TROPOPAUSE	33	7
V wind at tropopause	V WIND AT TROPOPAUSE	34	7
Wind shear at tropopause	SHEAR AT TROPOPAUSE	136	7
Height at tropopause	HEIGHT AT TROPOPAUSE	7	7
Temperature at flight levels	TEMP AT FD HEIGHTS	11	103
U wind at flight levels	U WIND AT FD HEIGHTS	33	103
V wind at flight levels	V WIND AT FD HEIGHTS	34	103
Freezing level height (above mean sea level)	HEIGHT OF FRZ LVL	7	4
Freezing level RH	REL HUMID AT FRZ LVL	52	4
Highest freezing level height	HIGHEST FREEZE LVL	7	204
Pressure in boundary layer (30 mb mean)	PRESS IN BNDRY LYR	1	116
Temperature in boundary layer (30 mb mean)	TEMP IN BNDRY LYR	11	116
Potential temperature in boundary layers (30 mb mean)	POT TMP IN BNDRY LYR	13	116
Dew point temperature in boundary layer (30 mb mean)	DWPT IN BNDRY LYR	17	116
Specific humidity in boundary layer (30 mb mean)	SPC HUM IN BNDRY LYR	51	116
RH in boundary layer (30 mb mean)	REL HUM IN BNDRY LYR	52	116
Moisture convergence in boundary layer (30 mb mean)	MST CNV IN BNDRY LYR	135	116
Precipitable water in boundary layer (30 mb mean)	P WATER IN BNDRY LYR	54	116
U wind in boundary layer (30 mb mean)	U WIND IN BNDRY LYR	33	116
V wind in boundary layer (30 mb mean)	V WIND IN BNDRY LYR	34	116
Omega in boundary layer (30 mb mean)	OMEGA IN BNDRY LYR	39	116
Visibility	VISIBILITY	20	1
Vegetation type	VEGETATION TYPE	225	1
Soil type	SOIL TYPE	224	1
Canopy conductance	CANOPY CONDUCTANCE	181	1
PBL height	PBL HEIGHT	221	1
Slope type	SLOPE TYPE	222	1
Snow depth	SNOW DEPTH	66	1
Liquid soil moisture	LIQUID SOIL MOISTURE	160	112
Snow free albedo	SNOW FREE ALBEDO	170	1
Maximum snow albedo	MAXIMUM SNOW ALBEDO	159	1
Canopy water evaporation	CANOPY WATER EVAP	200	1
Direct soil evaporation	DIRECT SOIL EVAP	199	1

Plant transpiration	PLANT TRANSPIRATION	210	1
Snow sublimation	SNOW SUBLIMATION	198	1
Air dry soil moisture	AIR DRY SOIL MOIST	231	1
Soil moist porosity	SOIL MOIST POROSITY	240	1
Minimum stomatal resistance	MIN STOMATAL RESIST	203	1
Number of root layers	NO OF ROOT LAYERS	171	1
Soil moist wilting point	SOIL MOIST WILT PT	219	1
Soil moist reference	SOIL MOIST REFERENCE	230	1
Canopy conductance - solar component	CANOPY COND SOLAR	246	1
Canopy conductance - temperature component	CANOPY COND TEMP	247	1
Canopy conductance - humidity component	CANOPY COND HUMID	248	1
Canopy conductance - soil component	CANOPY COND SOILM	249	1
Potential evaporation	POTENTIAL EVAP	145	1
Heat diffusivity on sigma surface	DIFFUSION H RATE S S	182	107
Surface wind gust	SFC WIND GUST	180	1
Convective precipitation rate	CONV PRECIP RATE	214	1
Radar reflectivity at certain above ground heights	RADAR REFL AGL	211	105

VAPOR

VAPOR is the **V**isualization and **A**nalysis **P**latform for **O**cean, Atmosphere, and Solar **R**esearchers. VAPOR was developed at NCAR to provide interactive visualization and analysis of numerically simulated fluid dynamics. The current (1.5) version of VAPOR has many capabilities for 3D visualization of WRF-ARW simulation output.

Basic capabilities of VAPOR with WRF-ARW output

- *Direct Volume rendering (DVR)*
  Any 3D variable in the WRF data can be viewed as a density. Users control transparency and color to view temperature, water vapor, clouds, etc. in 3D.

- *Flow*
  - Draw 2D and 3D streamlines and flow arrows, showing the wind motion and direction, and how wind changes in time.
  - Path tracing (unsteady flow) enables visualization of trajectories that particles take over time. Users control when and where the particles are released.
  - Flow images (image based flow visualization) can be used to provide an animated view of wind motion in a planar section, positioned anywhere in the scene.
  - Field line advection can be used to animate the motion of streamlines of any vector field in a moving wind field.

- *Isosurfaces*
  The isosurfaces of variables are displayed interactively. Users can control iso-values, color and transparency of the isosurfaces. Isosurfaces can be colored according to the values of another variable.

- *Contour planes and Probes*
  3D variables can be intersected with arbitrarily oriented planes. Contour planes can be interactively positioned. Users can interactively pinpoint the values of a variable and establish seed points for flow integration. Wind and other vector fields can be animated in the probe plane.

- *Two-dimensional variable visualization*
  2D (horizontal) WRF variables can be color-mapped and visualized in the 3D scene. They can be viewed on a horizontal plane in the scene, or mapped onto the terrain surface.

- *Animation*
  Control the time-stepping of the data, for interactive replaying and for recording animated sequences.

- *Image display*
  Tiff images can be displayed in the 3D scene. If the images are georeferenced (i.e. geotiffs) then they can be automatically positioned at the correct latitude/longitude coordinates. Images can be mapped to the terrain surface, or aligned to an axis-aligned plane. VAPOR also provides several utilities for obtaining geo-referenced images. Images can be downloaded from various Web Mapping Services (WMS's), obtaining political boundary maps, rivers, and satellite images. VAPOR also supports georeferencing and display of NCL plots from WRF output files. Images with transparency can be overlayed, enabling combining multiple layers of information.

- *Analysis capabilities*
  Derived variables can be calculated in IDL and interactively visualized in the 3D scene. Variables can also be calculated in other languages (e.g. NCL) and adjoined to the 3D visualization.

VAPOR requirements

VAPOR is supported on Linux, Mac, and Windows. VAPOR works best with a recent graphics card (say 1-2 years old). The advanced features of VAPOR perform best with nVidia or ATI graphics accelerators.

VAPOR is installed on NCAR visualization systems. Users with UCAR accounts can connect their (windows or Linux) desktops to the NCAR visualization systems using NCAR's vnc-based remote visualization services, to run VAPOR and visualize the results remotely. Instructions for using this are at:
http://www.cisl.ucar.edu/hss/dasg/services/docs/VAPOR.shtml.
Contact *dasg@ucar.edu* for assistance.

VAPOR support resources

The VAPOR website*:* *http://www.vapor.ucar.edu* includes software, documentation, example data, and links to other resources. The document "*Getting started with VAPOR and WRF*" *(http://www.vapor.ucar.edu/docs/usage/wrfstart/WRFGetStarted.pdf)* has an overview of the various documents that are useful in visualizing WRF data with VAPOR.

The VAPOR sourceforge website (*http://sourceforge.net/projects/vapor*) enables users to post bugs, request features, download software, etc.

Users of VAPOR on NCAR visualization systems should contact *dasg@ucar.edu* for support.

Users are encouraged to provide feedback. Questions, problems, bugs etc. should be reported to *vapor@ucar.edu*. The VAPOR development priorities are set by users as well as by the VAPOR steering committee, a group of turbulence researchers who are interested in improving the ability to analyze and visualize time-varying simulation results. Post a feature request to the VAPOR SourceForge website *(http://sourceforge.net/projects/vapor)*, or e-mail *vapor@ucar.edu* if you have requests or suggestions about improving VAPOR capabilities.

Basic steps for using VAPOR to visualize WRF-ARW data

1. Install VAPOR

VAPOR installers for Windows, Macintosh and Linux are available on the VAPOR download page, *http://www.vapor.ucar.edu/download*. For most users, a binary installation is fine. Installation instructions are also provided in the VAPOR documentation pages, *http://www.vapor.ucar.edu/docs/install*.

After VAPOR is installed, it is necessary to perform user environment setup on Unix or Mac, before executing any VAPOR software. These setup instructions are provided on the VAPOR binary install documentation pages, http://www.vapor.ucar.edu/docs/install.

2. Convert WRF output data to VAPOR

This process is described in detail in the VAPOR/WRF Data and Image Preparation Guide, http://www.vapor.ucar.edu/docs/usage/wrfprep/WRFsupport.pdf.

VAPOR datasets consist of (1) a metadata file (file type .vdf) that describes an entire VAPOR data collection, and (2) a directory of multi-resolution data files where the actual data is stored. The metadata file is created by the command *wrfvdfcreate*, and the multi-resolution data files are written by the command *wrf2vdf*. The simplest way to create a VAPOR data collection is as follows:

First issue the command:

```
wrfvdfcreate wrf_files metadata_file.vdf
```

where: *wrf_files* is a list of one or more wrf output files that you want to use. *metadata_file.vdf* is the name that you will use for your metadata file.

For example, if the entire data is in one wrfout d02 file one could issue the following command to create the metadata file "wrfout.vdf"::

```
wrfvdfcreate wrfout_d02_2006-10-25_18_00_00 wrfout.vdf
```

Then, to actually convert the data, issue the command:

```
wrf2vdf metadata_file.vdf wrf_files
```

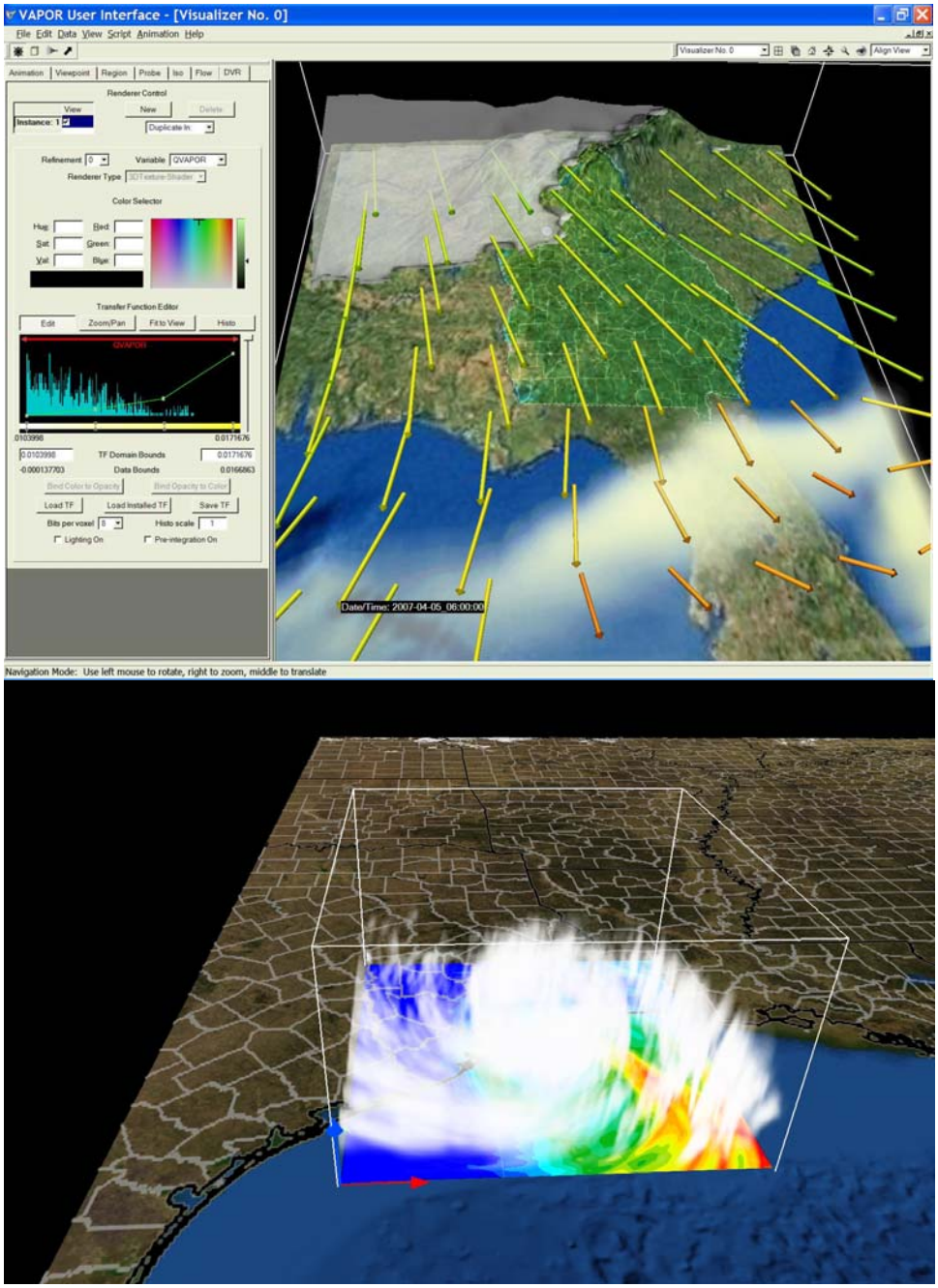
using the same arguments (in reversed order) as you used with *wrfvdfcreate*. Note that *wrf2vdf* does most of the work, and may take a few minutes to convert a large WRF dataset.

After issuing the above commands, all of the 2D and 3D variables on the spatial grid in the specified WRF output files will be converted, for all the time steps in the files. If you desire more control over the conversion process, there are many additional options that you can provide to *wrfvdfcreate* and *wrf2vdf*. Type the command with the argument "-help" to get a short-listing of the command usage. All data conversion options are detailed in section 1 of the VAPOR/WRF Data and Image Preparation Guide (http://www.vapor.ucar.edu/docs/usage/wrfprep/WRFsupport.pdf). Some of the options include:

- Calculation of derived variables such as vertical vorticity, temperature in Kelvin, normalized pressure, wind velocity.
- Overriding default volume dimensions and/or spatial extents.
- Converting only a subset of the WRF output time steps
- Converting a specific collection of variables.

4. Visualize the WRF data

From the command line, issue the command "*vaporgui*", or double-click the VAPOR desktop icon (on Windows or Mac). This will launch the VAPOR user interface. From the Data menu, choose "Load a dataset into default session", and select the metadata file that you associated with your converted WRF data.



To visualize the data, select a renderer tab (DVR, Iso, Flow, 2D, Image, or Probe), chose the variable(s) to display, and then, at the top of the tab, check the box labeled "Instance:1", to enable the renderer. For example, the above top image combines volume, flow and isosurface visualization with a terrain image. The bottom image illustrates hurricane Ike, as it made landfall in 2008. The Texas terrain has a map of US Counties applied to it, and an NCL image of accumulated rainfall is shown at ground level in the current region.

5. Read the VAPOR Documentation

For a quick overview of capabilities of VAPOR with WRF data, see Getting started with VAPOR and WRF, *http://www.vapor.ucar.edu/docs/usage/wrfstart/WRFGetStarted.pdf*.
Several documents on the VAPOR website *(http://www.vapor.ucar.edu) are* provided for visualization of WRF data. Additional resources are available in the VAPOR user interface to help users quickly get the information they need, and showing how to obtain the most useful visualizations:

-The *Georgia Weather Case Study* *(http://www.vapor.ucar.edu/docs/tutorial/georgia/GeorgiaCaseStudy.pdf)* provides a step-by-step tutorial, showing how to use most of the VAPOR features that are useful in WRF visualization.

- Conversion of WRF data and creation of georeferenced images are discussed in the *VAPOR/WRF Data and Image Preparation Guide*. *(http://www.vapor.ucar.edu/docs/usage/wrfprep/WRFsupport.pdf)*

- "*Using NCL with VAPOR to visualize WRF-ARW data*" *(http://www.vapor.ucar.edu/docs/tutorial/wrfncl/VAPOR-WRF-NCL.pdf)* is a tutorial that shows how to create georeferenced images from NCL plots, and to insert them in VAPOR scenes.

- Complete documentation of all capabilities of the VAPOR user interface is provided in the *VAPOR User Interface Reference Manual* *(http://www.vapor.ucar.edu/docs/reference/UIRef/ReferenceManual.pdf).*

- The *VAPOR Users' Guide for WRF Typhoon Research* *(http://www.vapor.ucar.edu/docs/tutorial/typhoon/Typhoon.pdf)* provides a tutorial for using VAPOR on typhoon data, including instructions for preparing satellites images and NCL plots to display in the scene..

- To understand the meaning or function of an element in the VAPOR user interface:
Tool tips: Place the cursor over a widget for a couple of seconds and a one-sentence description is provided.
Context-sensitive help: From the Help menu, click on "?Explain This", and then click with the left mouse button on a widget, to get a longer technical explanation of the functionality.

Chapter 10: Utilities and Tools

Table of Contents

Introduction

This chapter contains a number of short utilities to read and manipulate WRF-ARW data.

Also included in this chapter are references to some basic third part software, which can be used to view/change input and output data files.

read_wrf_nc

This utility allows a user to look at a WRF netCDF file at a glance.

What is the difference between this utility and the netCDF utility ncdump?

- This utility has a large number of options, to allow a user to look at the specific part of the netCDF file in question.
- The utility is written in Fortran 90, which will allow users to add options.
-

This utility can be used for both WRF-ARW and WRF-NMM cores.□□
It can be used for geogrid, metgrid and wrf input / output files.□□
Only 3 basic diagnostics are available, pressure / height / tk, these can be activated with the -diag option *(these are only available for wrfout files)*

Obtain the **read_wrf_nc utility** from the WRF Download page (*http://www.mmm.ucar.edu/wrf/users/download/get_source.html*)

Compile

The code should run on any machine with a netCDF library *(If you port the code to a different machine, please forward the compile flags to wrfhelp@ucar.edu)*

To compile the code, use the compile flags at the top of the utility.

e.g., *for a LINUX machine you need to type:*

```
pgf90  read_wrf_nc.f  -L/usr/local/netcdf/lib
   -lnetcdf  -lm  -I/usr/local/netcdf/include
   -Mfree  -o read_wrf_nc
```

If successful, this will create the executable: `read_wrf_nc`

Run

```
./read_wrf_nc  wrf_data_file_name  [-options]

options : [-h / help] [-att] [-m] [-M z] [-s]
          [-S x y z] [-v VAR] [-V VAR] [-w VAR]
          [-t t1 [t2]] [-times]
          [-ts xy X  Y  VAR VAR ....]
          [-ts ll  lat lon VAR VAR ....]
          [-lev z] [-rot] [-diag]
          [-EditData VAR]
```

Options:	*(Note: options [-att] ; [-t] and [-diag] can be used with other options)*
-h / help	Print help information.
-att	Print global attributes.
-m	Print list of fields available for each time, plus the min and max values for each field.
-M **z**	Print list of fields available for each time, plus the min and max values for each field. The min and max values of 3d fields will be for the **z** level of the field.
-s	Print list of fields available for each time, plus a sample value for each field. Sample value is taken from the middle of model domain.
-S **x y z**	Print list of fields available for each time, plus a sample value for each field. Sample value is at point **x y z** in the model domain.
-t **t1 [t2]**	Apply options only to times **t1** to **t2**. t2 is optional. If not set, options will only apply to **t1**.
-times	Print only the times in the file.

-ts	Generate time series output. A full vertical profile for each variable will be created. -ts xy X Y VAR VAR ….. will generate time series output for all VAR's at location X/Y -ts ll lat lon VAR VAR ….. will generate time series output for all VAR's at x/y location nearest to lat/lon
-lev **z**	Work only with option **–ts** Will only create a time series for level **z**
-rot	Work only with option **–ts** Will rotate winds to earth coordinates
-diag	Add if you want to see output for the diagnostics temperature (K), full model pressure and model height *(tk, pressure, height)*
-v **VAR**	Print basic information about field **VAR**.
-V **VAR**	Print basic information about field **VAR**, and dump the full field out to the screen.
-w **VAR**	Write the full field out to a file **VAR.out**
	Default Options are [-att –s]

SPECIAL option: -EditData VAR

This option allows a user to **read** a WRF netCDF file, **change** a specific field and **write** it BACK into the WRF netCDF file.
This option will CHANGE your CURRENT WRF netCDF file so TAKE CARE when using this option.
ONLY one field at a time can be changed. So if you need 3 fields changed, you will need to run this program 3 times, each with a different "VAR"
IF you have multiple times in your WRF netCDF file – **by default ALL times** for variable "VAR" WILL be changed. *If you only want to change one time period, also use the "-t" option.*

HOW TO USE THIS OPTION:

Make a COPY of your WRF netCDF file before using this option

EDIT the subroutine USER_CODE

ADD an IF-statement block for the variable you want to change. This is to prevent a variable getting overwritten by mistake.

For REAL data arrays, work with array "data_real" and for INTEGER data arrays, work with the array "data_int".

Example 1:
If you want to change all (all time periods too) values of U to a constant 10.0 m/s, you would **add** the following IF-statement:

```
  else if ( var == 'U') then
    data_real = 10.0
```

Example 2:
If you want to change a section of the LANDMASK data to SEA points:

```
  else if ( var == 'LANDMASK') then
    data_real(10:15,20:25,1) = 0
```

Example 3:
Change **all** ISLTYP category 3 values into category 7 values (NOTE this is an INTEGER field):

```
  else if ( var == 'ISLTYP') then
    where (data_int == 3 )
      data_int = 7
    end where
```

Compile and run program
You will be prompted if this is really what you want to do
ONLY the answer "yes" will allow the change to take effect

iowrf

This utility allows a user to do some basic manipulation on WRF-ARW netCDF files.

- The utility allows a user to thin the data; de-stagger the data; or extract a box from the data file.

Obtain the **iowrf utility** from the WRF Download page (*http://www.mmm.ucar.edu/wrf/users/download/get_source.html*)

Compile

The code should run on any machine with a netCDF *library (If you port the code to a different machine, please forward the compile flags to wrfhelp@ucar.edu)*

To compile the code, use the compile flags at the top of the utility.

e.g., *for a LINUX machine you need to type:*

```
pgf90 iowrf.f  -L/usr/local/netcdf/lib  -lnetcdf  -lm
      -I/usr/local/netcdf/include  -Mfree  -o iowrf
```

If successful, this will create the executable: `iowrf`

Run

```
./iowrf  wrf_data_file_name  [-options]

options : [-h / help] [-thina X] [-thin X] [-box {}]
          [-A] [-64bit]
```

-thina **X**	Thin the data with a ratio of 1:X Data will be averaged before being fed back
-thin **X**	Thin the data with a ratio of 1:X No averaging will be done
-box **{}**	Extract a box from the data file. X/Y/Z can be controlled independently. e.g., -box **x** 10 30 **y** 10 30 **z** 5 15 -box **x** 10 30 **z** 5 15 -box **y** 10 30 -box **z** 5 15
-A	De-stagger the data – no thinning will take place
-64bit	Allow large files (> 2GB) to be read / write

p_interp

This utility interpolates WRF-ARW netCDF output files to user specified pressure levels.

Obtain the **p_interp utility** from the WRF Download page (*http://www.mmm.ucar.edu/wrf/users/download/get_source.html*)

Compile

The code should run on any machine with a netCDF *library (If you port the code to a different machine, please forward the compile flags to wrfhelp@ucar.edu)*

To compile the code, use the compile flags at the top of the utility.

e.g., *for a LINUX machine you need to type:*

```
pgf90 p_interp.F90  -L/usr/local/netcdf/lib
      -lnetcdf  -lm  -I/usr/local/netcdf/include
      -Mfree  -o p_interp
```

If successful, this will create the executable: `p_interp`

Run

Edit the associated namelist.pinterp file *(see namelist options below),* and run

```
./p_interp
```

&io	
path_to_input	Default is "./"
input_name	File name(s) of wrfout files. *Use wild character if more than one file is processed.*
path_to_output	Default is "./"
output_name	If no name is specified the output will be written to *input_name_PLEV*
process	Indicate which fields to process. 'all' fields in wrfout file *(diagnostics PRES, TT, HGT & RH will automatically be calculated)*; 'list' of fields as indicated in 'fields'

fields	List of fields to process.
debug	Switch debug more on/off.
-64bit	Allow large files (> 2GB) to be read / write.
&interp_in	
interp_levels	List of pressure levels to interpolate data to
extrapolate	0 - set values below ground and above model top to missing values *(default)* 1 - extrapolate below ground, and set above model top to model top values
interp_method	1 - linear in p interpolation *(default)* 2 - linear in log p interpolation
unstagger_grid	Set to .True. so unstagger the data on output

TC Bogus Scheme

The ARW core for the WRF modeling system provides a simple Tropical Cyclone (TC) Bogussing scheme. It can remove an existing tropical storm, and may optionally bogus in a Rankine vortex for the new tropical storm. The input to the program is a single time-period and single domain of **`metgrid`** data, and a few namelist variables from the **`namelist.input`** file describing the bogus TC's location and strength. The output is also a **`metgrid`**-like file. The scheme is currently only set up to process isobaric data. After running the tc.exe program, the user must manually rename the files so that the **`real.exe`** program can read the modified input.

Namelist Options

The namelist information for the TC scheme is located in an optional namelist record **`&tc`**. Only a single domain is processed. Users with multiple domains should horizontally interpolate the generated meteorological fields to the fine-grid domains. Alternatively, users may run the **`tc.exe`** program on separate **`metgrid`** output files for different domains, though this is not recommended.

insert_bogus_storm	logical, insert a bogus storm
remove_storm	logical, remove an existing storm
num_storm	integer, number of storms to bogus, currently must be set to 1
latc_storm	real, latitude of bogus storm (+ north, - south)
lonc_storm	real, longitude of bogus storm (+ east, - west)
vmax_meters_per_second	real, maximum observed sustained wind speed (m/s)
rmax	real, radius from the cyclone center to where the maximum wind speed occurs (m)
vmax_ratio	real, scale factor for model's Rankine vortex

Note: If **`insert_bogus_storm`** is set to true then **`remove_storm`** should be set to false. If **`remove_storm`** is set to true then **`insert_bogus_storm`** should be set to false.

The value for **`vmax_ratio`** should be about 0.75 for a 45-km domain and about 0.90 for a 15-km domain. This is a representativeness scale factor. The observed maximum wind speed is not appropriate for an entire grid cell when the domain is fairly coarse.

For example, assume that a cyclone report came in with the storm centered at 25^{o} N and 75^{o} W, where the maximum sustained winds were observed to be 120 kts, with the maximum winds about 90 km from the storm center. With a 45-km coarse grid model domain, the namelist.input file would be:

```
&tc
insert_bogus_storm = .true.
remove_storm = .false.
latc_loc = 25.0
lonc_loc = -75.0
vmax_meters_per_second = 61.7
rmax = 90000.0
vmax_ratio = 0.75
/
```

Program tc.exe

The program **tc.exe** is automatically built along with the rest of the ARW executables. However this is a serial program. For the time being, it is the best to build this program using serial and no-nesting options.

Running tc.exe

1) Run all of the WPS programs as normal (**geogrid**, **ungrib**, and **metgrid**).
2) As usual, link in the metgrid output files into either the **test/em_real** or the **run** directory
3) Edit the **namelist.input** file for usage with the **tc.exe** program. Add in the required fields from the **&tc** record, and only process a single time period.
4) Run tc.exe
5) Rename the output file, **auxinput1_d01_<date>** to the name that the **real.exe** program expects, **met_em.d01.<date>**, note that this will overwrite your original **metgrid.exe** output file for the initial time period.
6) Edit the **namelist.input** file to process all of the time periods for the **real.exe** program.

v_interp

This utility can be used to add vertical levels in WRF-ARW netCDF input. An example of the usage would be one-way nesting via program `ndown`. Since program `ndown` does not do 'vertical nesting' prior to Version 3.2, namely adding vertical levels, this program can be used after running `ndown` to achieve the same results. Starting from Version 3.2, vertical levels may be added in program `ndown` via namelist option '`vert_refine_fact`', which allows one to refine vertical levels by an integer factor.

The **v_interp** utility program can be obtained from the WRF Download page (*http://www.mmm.ucar.edu/wrf/users/download/get_source.html*)

Compile

The code should be easily built and run on any machine with a netCDF library. To compile the code, use the compile flags shown at the top of the utility program.

e.g., *for a LINUX machine and pgf90 compiler, one may type:*

```
pgf90 v_interp.f  -L/usr/local/netcdf/lib -lnetcdf \
      -I/usr/local/netcdf/include  \
      -Mfree  -o v_interp
```

If successful, this will create the executable: `v_interp`

Run

Edit the namelist file `namelist.v_interp` *(see namelist options below)* for the number of new vertical levels (`nvert`) and the new set of levels (`nlevels`). To find out the existing model levels, check the original WRF `namelist.input` file used to create the input files, or type the following:

```
ncdump –v ZNW wrfinput_d01
```

The executable takes two arguments on the command line:

```
./v_interp file file_new
```

where `file` is the input file you want to add the vertical levels to, and `file_new` is the output file that contains more vertical levels. To run the program for `wrfinput` file, type

```
./v_interp wrfinput_d01 wrfinput_d01_new
```

For `wrfbdy` file, type

```
./v_interp wrfbdy_d01 wrfbdy_d01_new
```

namelists:

&newlevels	
nvert	Number of new vertical levels (statggered)
nlevels	Values of new model levels

Program Notes:

When adding vertical levels, please keep the first and the last half levels the same as in the input file itself. Problem may occur if levels are added outside the range.

For wrfbdy file, please keep the input file name as wrfbdy_* since the program keys on the file name in order to do the interpolation for special boundary arrays.

proc_oml.f

This utility may be used to process 3D HYCOM (http://www.hycom.org) ocean model temperature data in netCDF format to produce initial ocean mixed layer depth field (`H0ML`) for use in WRF simulation that uses the simple ocean mixed layer model option (`omlcall` = 1, and `oml_hml0` < 0). The program estimates two fields from the HYCOM data: 1) effective mixed layer depth based on the idea of ocean heat content (`H0ML`); and 2) mean ocean temperature in the top 200 m depth (`TMOML`). This is used as lower limit for cooling SST in the wake of a hurricane.

To download the **proc_oml.f** utility, please see
http://www.mmm.ucar.edu/wrf/users/hurricanes/util.html

Compile

To compile the code, use the compile flags shown at the top of the utility program. For example, for a LINUX machine and pgf90 compiler one may type*:*

```
pgf90 proc_oml.f  -L/usr/local/netcdf/lib -lnetcdf \
      -I/usr/local/netcdf/include -Mfree  -o proc_oml.f
```

If successful, this will create the executable: `proc_oml`

Run

To run the program, type

`./proc_oml` *`ocean-data-file.nc yyyymmddhh`*

where '`ocean-data-file.nc`' is the HYCOM ocean data file, and `yyyymmddhh` is the 10-digit date when the data is valid for (e.g. `2005082700`). Successfully running the program will produce an output file `MLD`, which is in intermediate format as if it were produced by `WPS/ungrib` program.

To use this field in `WPS/metgrid`, add it to '`constant_name`' as below:

```
constant_name = 'MLD',
```

V3.2 WPS/metgrid has the additional fields in METGRID.TBL for proper horizontal interpolation. For more information, please refer to presentation at http://www.mmm.ucar.edu/wrf/users/tutorial/hurricanes/AHW_nest_ocean.pdf

Tools

Below is a list of tools that are freely available that can be used very successfully to manipulate model data (both WRF model data as well as other GRIB and netCDF datasets).

Converting Graphics

ImageMagick

ImageMagick is a software suite to create, edit, and compose bitmap images. It can read, convert and write images in a variety of formats (over 100) including DPX, EXR, GIF, JPEG, JPEG-2000, PDF, PhotoCD, PNG, Postscript, SVG, and TIFF. Use ImageMagick to translate, flip, mirror, rotate, scale, shear and transform images, adjust image colors, apply various special effects, or draw text, lines, polygons, ellipses and B_zier curves.

The software package is freely available from, *http://www.imagemagick.org*. Download and installation instructions are also available from this site.

Examples of converting data with ImageMagick software:

```
convert  file.pdf     file.png
convert  file.png     file.bmp
convert  file.pdf     file.gif
convert  file.ras     file.png
```

ImageMagick cannot convert ncgm (NCAR Graphics) file format to other file formats.

Converting ncgm (NCAR Graphics) file format

NCAR Graphics has tools to convert ncgm files to raster file formats. Once files are in raster file format, ImageMagick can be used to translate the files into other formats.

For *ncgm* files containing a single frame, use ***ctrans***.

```
ctrans  -d sun  file.ncgm  file.ras
```

For *ncgm* files containing multiple frames, first use ***med*** (metafile frame editor) and then *ctrans*. ***med*** will create multiple single frame files called *medxxx.ncgm*

```
med -e '1,$ split $' file.ncgm
ctrans  -d sun_ med001.ncgm > med001.ras
```

Design WRF model domains

WPS/util/plotgrids.exe, can be used to display model domains before WPS/geogrid.exe is run.

This utility reads the domain setup from namelist.wps and creates an ncgm file that can be viewed with the NCAR Graphics command "idt", e.g.,

```
idt gmeta
```

Read more about this utility in Chapter 3 of this Users Guide.

Display ungrib (intermediate) files

WPS/util/plotfmt.exe, can be used to display intermediate files created by WPS/ungrib.exe.

If you have created intermediate files manually, it is a very good practice to use this utility to display the data in your files first before running WPS/metgrid/exe. ***Note**: If you plan on manually creating intermediate files, refer to http://www.mmm.ucar.edu/wrf/OnLineTutorial/WPS/IM_files.htm for detailed information about the file formats and sample programs.*

This utility reads intermediate files and creates an ncgm file that can be viewed with the NCAR Graphics command "idt", e.g.,

```
idt gmeta
```

Read more about this utility in **Chapter 3** of this Users Guide.

netCDF data

netCDF stands for **ne**twork **C**ommon **D**ata **F**orm.
Most of the information below can be used for WRF netCDF data as well as other netCDF datasets.
netCDF is one of the current supported data formats chosen for WRF I/O API.

Advantages of using netCDF?

Most graphical packages support netCDF file formats
netCDF files are platform-independent (big-endian / little-endian)
A lot of software already exists which can be used to process/manipulate netCDF data

Documentation:
http://www.unidata.ucar.edu/ (General netCDF documentation)
http://www.unidata.ucar.edu/software/netcdf/fguide.pdf (NETCDF User's Guide for FORTRAN)

Utilities:
ncdump
Part of the netCDF libraries. Reads a netCDF file and prints information about the dataset. e.g.

`ncdump -h` ***`file`*** *(print header information)*
`ncdump -v` ***`VAR file`*** *(print header information and the full field VAR)*
`ncdump -v Times file` *(a handy way to see how many times are available in a WRF output file)*

ncview
Display netCDF data graphically. No overlays, no maps and no manipulation of data possible.
http://meteora.ucsd.edu/~pierce/ncview_home_page.html

ncBrowse
Display netCDF data graphically. Some overlays, maps and manipulation of data are possible.
http://www.epic.noaa.gov/java/ncBrowse/

read_wrf_nc
A utility to display basic information about WRF netCDF files.

iowrf
A utility to do some basic file manipulation on WRF-ARW netCDF files.

p_interp
A utility to interpolate WRF-ARW netCDF output files to user specified pressure levels.

netCDF operators
http://nco.sourceforge.net/
Stand alone programs to, which can be used to manipulate data (performing grid point averaging / file differencing / file 'appending'). *Examples of the available operators are ncdiff, ncrcat, ncra, and ncks.*

ncdiff
Difference two file, e.g.

```
ncdiff  input1.nc input2.nc output.nc
```

ncrcat
Write specified variables / times to a new file, e.g.

```
ncrcat -v RAINNC wrfout* RAINNC.nc
ncrcat -d Time,0,231 –v  RAINNC  wrfout* RAINNC.nc
```

ncra
Average variables and write to a new file, e.g.

```
ncra -v OLR  wrfout* OLR.nc
```

ncks (nc kitchen sink)
Combination of NCO tools all in one (handy: one tool for multiple operations).
One specifically handy use of this tool is to split large files into smaller files, e.g.

```
ncks –A –F –d Time,1,1 wrfout* -o wrfout_time1.nc
```

GRIB data

Documentation

http://dss.ucar.edu/docs/formats/grib/gribdoc/ (Guide to GRIB 1)
http://www.nco.ncep.noaa.gov/pmb/docs/grib2/grib2_doc.shtml (Guide to GRIB2)
http://www.nco.ncep.noaa.gov/pmb/docs/grib2/GRIB2_parmeter_conversion_table.html (GRIB2 - GRIB1 parameter conversion table)

GRIB codes

It is important to understand the GRIB codes to know which fields are available in your dataset. For instance, NCEP uses the GRIB1 code 33 for the U-component of the wind, and 34 for the V-component. *Other centers may use different codes, so always obtain the GRIB codes from the center you get your data from.*

GRIB2 uses 3 codes for each field - **product**, **category** and **parameter**.
We would most often be interested in **product 0** (*Meteorological products*).
Category refers to the type of field, e.g., category 0 is temperature, category 1 is moisture and category 2 is momentum. **Parameter** is the field number.
So whereas GRIB1 only uses code 33 for the U-component of the wind, GRIB2 will use 0,2,2, for the U-component, and 0,2,3 for the V-component.

Display GRIB header/field information

GRIB1 data

WPS/util/g1print.exe
wgrib *(http://www.cpc.ncep.noaa.gov/products/wesley/wgrib.html)*

GRIB2 data
WPS/util/g2print.exe
wgrib2 *(http://www.cpc.ncep.noaa.gov/products/wesley/wgrib2/)*

Convert GRIB1 data to netCDF format
ncl_grib2nc *(http://www.ncl.ucar.edu/Document/Tools)*

Model Verification

MET is designed to be a highly configurable, state-of-the-art suite of verification tools. It was developed using output from the Weather Research and Forecasting (WRF) modeling system but may be applied to the output of other modeling systems as well.

MET provides a variety of verification techniques, including:

- Standard verification scores comparing gridded model data to point-based observations
- Standard verification scores comparing gridded model data to gridded observations
- Object-based verification method comparing gridded model data to gridded observations

http://www.dtcenter.org/met/users/index.php

Appendix A: WRF-Fire

Table of Contents

Introduction

A wildland fire module has been added to WRF to allow users to model the growth of a wildland fire and the dynamic feedbacks with the atmosphere. It is implemented as a physics package with two-way coupling between the fire behavior and the atmospheric environment allowing the fire to alter the atmosphere surrounding it, i.e. 'create its own weather'. Other documents describe the derivation of the model – here we address the mechanics, options, parameters, and datasets for using this module.

The wildland fire module is currently a simple two-dimensional model of a surface fire. The user specifies the time, location, and shape of a fire ignition. The evolution of the fireline, the interface enclosing the burning region, is implemented by the level set method. The level set function is advanced by the Runge-Kutta method of order 2, with spatial discretization by the Godunov method. The rate at which this interface expands is calculated at all points along it using a point-based semi-empirical formula for estimating the rate of spread of the surface fire based upon the Rothermel formula, which calculates the fire rate of spread as a function of local fuel conditions, wind, and terrain slope. Importantly, the winds used to drive the fire are interpolated from nearby low-level wind velocities, which are themselves perturbed by the fire. Once the fireline has passed by,

the ignited fuel continues to burn - the mass of fuel is assumed to decay exponentially with time after ignition, the rate depending on the size of the fuel particles making up the fuel complex. The fuel burned in each time step is converted to sensible and latent heat source terms for the lowest levels of the WRF atmospheric model state, where the water vapor source arises from the intrinsic moisture in cellulosic fuels and the additional moisture, the fuel moisture content, held by fuels The fire may not progress to locations where the local fuel moisture content is greater than the moisture content of extinction,

Additional parameters and datasets beyond a standard WRF atmospheric simulation are required and are described here, The surface fuel available to be burned at each point is categorized using the Anderson classification system for "fuel models" (3 grass-dominated types, 4 shrub-dominated types, 3 types of forest litter, and 3 levels of logging slash) which we will henceforth refer to as "fuel categories" to limit confusion. Each of these fuel categories is assigned a set of typical properties consisting of the fuel load (the mass per unit area) and numerous physical properties having to do with fuel geometry, arrangement, and physical makeup. The user may make the fuels spatially homogeneous by using one fuel category for the whole domain, alter fuel properties, add custom fuel categories, or (for real data experiments) project a spatially heterogeneous map of fuel categories onto the domain from fuel mapping datasets. The user also sets the number of ignitions, their time, location, and shape, and the fuel moisture content, an important factor in fire behavior.

One time step of the fire model is performed for every WRF time step. The fire model runs on a refined grid, which covers the same region as the innermost WRF domain. The fire module supports both distributed and shared memory parallel execution.

Other References

- WRF-Fire documentation, in particular the Technical description, available at http://www.openwfm.org/wiki/WRF-Fire_documentation

- Users may wish to review Anderson's fuel classification system (Anderson, H. E. 1982. *Aids to determining fuel models for estimating fire behavior.* USDA For. Serv. Gen. Tech. Rep. INT-122, 22p. Intermt. For. and Range Exp. Stn., Ogden, Utah 84401) at http://www.fs.fed.us/rm/pubs_int/int_gtr122.pdf .

- The original report introducing Rothermel's semi-empirical formulas (Rothermel, R. C. 1972. *A mathematical model for predicting fire spread in wildland fuels.* Res. Pap. INT-115. Ogden, UT: U.S. Department of Agriculture, Intermountain Forest and Range Experiment Station. 40 p.) is available at http://www.treesearch.fs.fed.us/pubs/32533 .

WRF-Fire in idealized cases

To install WRF-Fire, follow the installation instructions in Chapter 5 to configure WRF and set up the environment. For an idealized case, use

```
./compile em_fire
```

to build WRF for one of the several supplied ideal examples. This will create the links `wrf.exe` and `ideal.exe` in the directory `test/em_fire`. The examples are in its subdirectories. The links `wrf.exe` and `ideal.exe` in the subdirectories point to the parent directory.

To run the `small` idealized example, type

```
cd test/em_fire

cp examples/small/* .

./ideal.exe

./wrf.exe
```

Other idealized examples supplied in `test/em_fire/examples` directory are `hill`, `nested`, and `fireflux`. Each directory contains all files needed to run the example, namely `namelist.input`, `namelist.fire`, and `input_sounding`.

The file `namelist.input` contains an additional section `&fire` with parameters of the fire model and ignition coordinates. The file `namelist.fire` contains an additional namelist used to enter custom fuel properties.

Fire variables in namelist.input

Variable names	Value	Description
`&domains`		Domain definition
`sr_x`	10	Fire mesh is 10 times finer than the innermost atmospheric mesh in the *x* direction. This number must be even.
`sr_y`	10	Fire mesh is 10 times finer than the innermost atmospheric mesh in the *y* direction. This number must be even.

`&fire`		Fire control
`ifire`	0	The fire model skipped
	2	The fire model runs
`fire_fuel_read`	0	How to set the fuel data
		-1: real data from WPS
		0: set to `fire_fuel_cat` everywhere
		1: vegetation by altitude
`fire_num_ignitions`	3	Number of ignition lines, max. 5 allowed
`fire_ignition_start_x1`	1000.	*x* coordinate of the start point of the ignition line 1. All ignition coordinates are given in m from the lower left corner of the innermost domain
`fire_ignition_start_y1`	500.	*x* coordinate of the start point of the ignition line 1
`fire_ignition_end_x1`	1000.	*y* coordinate of the end point of the ignition line 1. Point ignition (actually a small circle) is obtained by specifying the end point the same as the start point.
`fire_ignition_end_y1`	1900.	*y* coordinate of the end point of the ignition line 1
`fire_ignition_radius1`	18.	Everything within 18 meters from the ignition location will be ignited.
`fire_ignition_time1`	2.	Time of ignition in s since the start of the run
`fire_ignition_start_x2` … `fire_ignition_time5`		Up to 5 ignition lines may be given. Ignition parameters with the number higher than `fire_num_ignitions` are ignored.
`fire_print_msg`	1	0: no messages from the fire scheme
		1: progress messages from the fire scheme
`fire_print_file`	0	0: no files written (leave as is)
		1: fire model state written every 10 s into files that can be read in Matlab. See `wrf/doc/README_vis.txt` in the developers' version.

There are several more variables in the namelist for developers' use only to further develop and tune the numerical methods. ***Leave as is*** unless directed by the developers.

namelist.fire

This file serves to redefine the fuel categories if the user wishes to alter default fuel properties.

Variable names	Description
`&fuel_scalars`	Scalar fuel constants
`cmbcnst`	The energy released per unit fuel burned for cellulosic fuels (constant, 1.7433e7 J kg^{-1}).
`hfgl`	The threshold heat flux from a surface fire at which point a canopy fire is ignited above (in W m^{-2}).
`fuelmc_g`	Surface fuel, fuel moisture content (in percent expressed in decimal form, from 0.00 – 1.00).
`fuelmc_c`	Canopy fuel, fuel moisture content (in percent expressed in decimal form, from 0.00 – 1.00).
`nfuelcats`	Number of fuel categories defined (default: 13)
`no_fuel_cat`	The number of the dummy fuel category specified to be used where there is 'no fuel'
`&fuel_categories`	Domain specifications
`fgi`	The initial mass loading of surface fuel (in kg m^{-2}) in each fuel category
`fueldepthm`	Fuel depth (m)
`savr`	Fuel Surface-area-to-volume-ratio (m^{-1})
`fuelmce`	Fuel moisture content of extinction (in percent expressed in decimal form, from 0.00 – 1.00).
`fueldens`	Fuel particle density lb ft^{-3} (32 if solid, 19 if rotten)
`st`	Fuel particle total mineral content. (kg minerals/kg wood)
`se`	Fuel particle effective mineral content. (kg minerals – kg silica)/kg wood
`weight`	Weighting parameter that determines the slope of the mass loss curve. This can range from about 5 (fast burnup) to 1000 (40% decrease in mass over 10 minutes).
`fci_d`	Initial dry mass loading of canopy fuel (in kg m^{-2})
`fct`	The burnout time of canopy fuel once ignited (s)
`ichap`	Is this a chaparral category to be treated differently using an empirical rate of spread relationship that depends only on windspeed? (1: yes, this is a chaparral category and should be treated differently; 0: no, this is not a chaparral category or should not be treated differently). Primarily used for Fuel Category 4.

Running WRF-Fire on real data

Building the code

Running WRF with real data is a complicated process of converting data formats and interpolating to the model grid. This process is simplified by the WRF Preprocessing System (WPS). The purpose of this section is to summarize the use of this system and to highlight the differences in its use between fire and ordinary atmospheric simulations. For more complete documentation of WPS, see Chapter 3 of the WRF-ARW User's Guide.
WPS consists of three utility programs: `geogrid.exe`, `ungrib.exe`, and `metgrid.exe`. Each program is designed to take existing data sets and convert/interpolate them into an intermediate format. The build system for WPS is similar to that of WRF. NetCDF must be installed and the environment variable NETCDF should be set to the installation prefix. Run the configure script in the main WPS directory, pick a configuration option from the list, and then run compile. Note that WRF itself must be built prior to compiling WPS. In addition, the build process assumes that WRF exists in `../WRFV3/`. WRF should be configured as described in Section 3 and compiled with the command

```
./compile em_real >& compile.log
```

The WPS can be configured from inside the top level directory wrf-fire/WPS with the command

```
./configure
```

and compiled in the same directory with the command

```
./compile >& compile.log
```

Upon successful completion the three binaries listed above should exist in the current directory.
Because the WPS programs are, for the most part, not processor intensive, it is not generally necessary to compile these programs for parallel execution, even if they do support it. Typical usage of WRF with real data involves doing all of the preprocessing work either locally on a workstation or on the head node of a supercomputer. The intermediate files are all architecture independent, so they can be transferred between computers safely. If you intend to use a supercomputer for the main simulation, it is advisable to generate the WPS output locally and transfer the met_em files to the computer you will be using for WRF-Fire. The met_em files are much smaller than the wrfinput and wrfbdy files and can be transported easily. This also eases the process of dealing with the dependencies of the python scripts described below because it may not be easy or even possible to meet these requirements on a shared parallel computer.

Fire variables in namelist.wps

The simulation domain is described in the file `namelist.wps`. This namelist contains four sections, one for each of the main binaries created in WPS and one shared among them all. This file, as distributed with WRF-Fire, is set up for a test case useful for testing, but in general one needs to modify it for each simulation domain. The following table lists namelist options that can be modified. Other options in this file are generally not necessary to change for WRF-Fire simulations. See the WRF-ARW User's Guide for more information.

Variable names	Description
`&share`	Shared namelist options
`max_dom`	Number of nested domains to use
`start_date/end_date`	Starting/ending date and time to process atmospheric data in the format YYYY-MM-DD_hh:mm:ss. These times should coincide with reanalysis cycles for your atmospheric data (hours 00,03,06,09,12, etc. for 3 hour NARR data). The simulation window in which you are interested in running must be inside this interval.
`Subgrid_ratio_[xy]`	The refinement ratio from the atmospheric grid to the fire grid.
`interval_seconds`	Number of seconds between each atmospheric dataset. (10800 for 3 hour NARR data)
`&geogrid`	Domain specifications
`parent_id`	When using nested grids, the parent of the current grid, or 0 if it is the highest level.
`parent_grid_ratio`	The refinement ratio from the parent grid (ignored for top level grid) (only 3 or 5 is supported by WRF)
`[ij]_parent_start`	The indices on the parent grid of the lower left corner of the current grid (ignored for top-level grid)
`E_we/e_sn`	The size of the grid in the x/y axis
`dx/dy`	Resolution of the grid in the x/y axis
`map_proj, true_lat[12], stand_lon`	Projection specifications. Lambert is typically used for central latitudes such as the continental US. For small domains, the projection used does not matter much.
`ref_x/ref_y`	Grid index of a reference point with known geographic location. Defaults to the center of the domain.
`ref_lon/ref_lat`	The location (longitude/latitude) of the reference point.
`geog_data_path`	Absolute or relative path to geogrid data released with WPS (http://www.mmm.ucar.edu/wrf/src/wps_files/geog_v3.1.tar.gz)

Geogrid

The geogrid executable acts exclusively on static datasets (those that don't change from day to day) such as surface elevation and land use. Because these datasets are static, they

can be obtained as a single tarball from the main WPS distribution website in resolutions of 10 minutes, 2 minutes, and 30 seconds. The geogrid executable extracts from these global data sets what it needs for the current domain. While resolutions of this magnitude are acceptable for ordinary atmospheric simulations, these datasets are too coarse for a high-resolution fire simulation. In particular, a WRF-Fire simulation will require two additional data sets not present in the standard data tarball.

NFUEL_CAT

The variable NFUEL_CAT contains Anderson 13 fuel category data. This data can be obtained for the US from the USGS seamless data access server at: http://landfire.cr.usgs.gov/viewer/. Using the zooming and panning controls, the user can select the desired region with LANDFIRE 13 Anderson Fire Behavior Fuel Models box selected. This will open a new window where the user can request the data in specific projections and data formats.

ZSF

The variable ZSF contains high resolution terrain height information similar to that in the HGT variable present in atmospheric simulations; however, the standard topographical data set is only available at a maximum resolution of 30 arc seconds (about 900 meters). For a WRF-Fire simulation, data resolution of at least 1/3 of an arc second is desirable. Such a dataset is available for the US at http://seamless.usgs.gov/. This is another USGS seamless data access server similar to that of LANDFIRE. The desired dataset on this server is listed under elevation and is called 1/3" NED.

Conversion to geogrid format

Once one has collected the necessary data from USGS servers or elsewhere, it is necessary to convert it from the given format (such as geotiff, arcgrid, etc) into geogrid format. The format specification of the geogrid format is given in the WPS section of the WRF users guide. The process of this conversion is somewhat technical; however, work is in progress to automate it. See the openwfm wiki (http://www.openwfm.org/wiki) for the latest information and links to helper scripts and source code.

Editing GEOGRID.TBL

In order to include your custom data into the WPS output, you must add a description of it in the GEOGRID.TBL file, which is located, by default, in the geogrid subdirectory of the main WPS distribution. In addition to the standard options described in the WPS users guide, there is one additional option that is necessary for defining data for fire grid variables. For them, there is a subgrid option, which is off by default. For fire grid data, one should add the option subgrid=yes to indicate that the variable should be defined on a refined subgrid with a refinement ratio defined by the subgrid_ratio_[xy] option the wps namelist. For example, typical table entries would appear as follows:

```
==============================
name=NFUEL_CAT
        priority=1
        dest_type=categorical
        dominant_only=NFUEL_CAT
        z_dim_name=fuel_cat
        halt_on_missing=yes

interp_option=default:nearest_neighbor+average_16pt+search
        rel_path=default:landfire/
        subgrid=yes
==============================
name = ZSF
        priority = 1
        dest_type = continuous
        halt_on_missing=yes
        interp_option = default:four_pt
        rel_path=default:highres_elev/
        subgrid=yes
```

This table assumes that the converted data resides as a subdirectory of the standard data directory given in the namelist under the option geog_data_path. The NFUEL_CAT data should reside in landfire/ and ZSF in highres_elev/. In general, the only options that should be modified by the user are the rel_path or abs_path options.
Once the data has been obtained and converted and the geogrid table has been properly set up, the user can run:
./geogrid.exe
which will create files such as geo_em.d01.nc that contain the interpolated static data fields.

Ungrib and Metgrid

The ungrib executable performs initial processing on atmospheric data. There are many different datasets that can be used as input to ungrib. One must obtain this data manually for a given simulation. Because fire simulations will be at a much higher resolution than most atmospheric simulations, it is advisable to get as high resolution data as possible. The 32 km resolution data from the North American Regional Reanalysis (NARR) is likely a good choice. This data is available freely from https://dss.ucar.edu/datazone/dsszone/ds608.0/NARR/3HRLY_TAR/. For real data WRF runs, three individual datasets from this website are required: 3d, flx, and sfc. To use them, download the files for the appropriate date/time and extract them somewhere on your filesystem. The files have the naming convention, NARR3D_200903_0103.tar. NARR indicates it comes from the NARR model, 3D indicates that it is the atmospheric data fields, and 200903_0103 indicates that it contains data from March 1st through 3rd of 2009. Once these files are extracted, they must be linked into the main WPS directory with the command link_grib.csh. It takes as arguments all of the files extracted from the dataset. For example, if you extracted these files to `/home/joe/mydata`, then you would issue the command:

```
./link_grib.csh /home/joe/mydata/*
```

into the top level WPS directory. Each atmospheric dataset requires a descriptor table known as a variable table to be present. WPS comes with several variable tables that work with most major data sources. These files reside in `WPS/ungrib/Variable_Tables/`. The appropriate file must be symlinked into the top level WPS directory as the file Vtable. For NARR data, type:

```
ln -sf ungrib/Variable_Tables/Vtable.NARR Vtable
```

Once this has been done, everything should be set up properly to run the ungrib command:

```
./ungrib.exe
```

Finally, the program metgrid combines the output of ungrib and geogrid to create a series of files, which can be read by WRF's real.exe. This is accomplished by

```
./metgrid.exe
```

Assuming everything completed successfully, you should now have a number of files named something like `met_em.d01.2009-03-01_12:00:00.nc`. These should be copied or linked to your `WRFV3/test/em_real` directory. If any errors occur during execution of ungrib or metgrid, then make sure you have downloaded all of the necessary atmospheric data and that the variable table and namelist are configured properly. See the WRF-ARW User's Guide and the user's forum at http://forum.wrfforum.com/ for many helpful hints at using various datasets.

Running real case and WRF-Fire

First copy or link the met_em files generated by metgrid into test/em_real. If the simulation is being done locally, this can be accomplished by running in `wrf-fire/WRFV3/test/em_real`

```
ln -sf ../../../WPS/met_em* .
```

The namelist for WRF in the file `namelist.input` must now be edited to reflect the domain configured in WPS. In addition to the fire-specific settings listed in Section 4.3 regarding the ideal simulation, a number of other settings must be considered as listed below. See Chapter 5 for more details on these settings.

Variable	Description
`&time_control`	
`start_xxx/end_xxx`	These describe the starting and ending date and time of the simulation. They must coincide with the start_date/end_date given in namelist.wps.
`run_xxx`	The amount of time to run the simulation.
`interval_seconds`	Must coincide with interval seconds from namelist.wps.

`restart_interval`	A restart file will be generated every x minutes. The simulation can begin from a restart file rather than wrfinput. This is controlled by the namelist variable 'restart'.
`&domains`	All grid settings must match those given in the geogrid section of namelist.wps.
`num_metgrid_levels`	The number of vertical levels of the atmospheric data being used. This can be determined from the met_em files: `ncdump -h met_em* | grep 'num_metgrid_levels ='`
`sr_x/sr_y`	Fire grid refinement. Must match that given in namelist.wps as subgrid_ratio_x/subgrid_ratio_y.
`p_top_requested`	The default is 5000, but may need to be edited if there is an error executing real. If so, just set this to whatever it tells you in the error message.

Once the namelist is properly configured, run the real executable:

```
./real.exe
```

and then run wrf:

```
./wrf.exe
```

Fire state variables

A number of array variables were added to the registry to the WRF state in order to support the fire model. They are available in the `wrfout*` files created when running WRF. All fire array variables are based at the centers of the fire grid cells. Their values in the strips at the upper end of width `sr_x` in the *x* direction and `sr_y` in the *y* direction are unused and are set to zero by WRF.

The following variables can be used to interpret the fire model output.

`LFN`	level set function. Node (i,j) is on fire if LFN(i,j)<=0
`FXLONG, FXLAT`	longitude and latitude of the nodes
`FGRNHFX`	ground heat flux from the fire (W/m^2), averaged over the cell
`FGRNQFX`	ground heat flux from the fire (W/m^2), averaged over the cell
`ZSF`	terrain elevation above sea level (m)
`UF,VF`	surface wind

FIRE_AREA	approximate part of the area of the cell that is on fire, between 0 and 1

WRF-Fire software

This section is intended for programmers who wish to modify or extend the fire module.

WRF-Fire coding conventions

The fire model resides in WRF physics layer and conforms to *WRF Coding Conventions*, which can be found at http://www.mmm.ucar.edu/wrf/WG2/WRF_conventions.html The purpose of the conventions is to produce a transparent, fast, and maintainable code that runs in parallel without any effort on the side of the programmer of the physics layer routines. The fire code maintains the conventions as they apply to on atmospheric grids, adapts them to 2D surface-based computations, and follows analogous conventions on the fire grid. In particular, the fire code may not maintain any variables or arrays that persist between calls, and may not use common blocks, allocatable variables, or pointer variables. Work arrays with variable bounds may be declared only as automatic; thus, they are freed between on exit from the subroutine where they are declared. All grid-sized arrays that should persist between calls to the fire code must be created in WRF through the registry mechanism, and passed to the fire code as arguments.

In addition, the fire code may not call any WRF routines directly but only through a utility layer. This is so that the fire code can be easily run standalone or coupled with another weather code. All variables in the fire code are based at grid centers. Grid dimensions are passed in argument lists as

```
ifds,ifde,jfds,jfde, & ! fire domain dims
ifms,ifme,jfms,jfme, & ! fire memory dims
ifps,ifpe,jfps,jfpe, & ! fire patch dims (may be omitted)
ifts,ifte,jfts,jfte, & ! fire tile dims
```

Atmosphere grid 2D variables are declared with `dimension(ims:ime, jms:jme)`. Fire grid variables are declared with `dimension(ifms:ifme, jfms:jfme)`. Loops on the fire grid are always over a tile. The index variable names, the order of the loops, and the bounds are required exactly as in the code fragment below.

```
do j=jfts,jfte
     do i=ifts,ifte
               fire_variable(i,j)=…
```

In loops that need to index more than one grid at the same time (such as computations on a submesh, or interpolation between atmosphere and fire) the index variable names must always begin with `i j`.

Parallel execution

In the fire code, all computational subroutines are called from a thread that services a single tile. There is no code running on a patch. Loops may update only array entries within in the tile but they may read other array entries in adjacent tiles, for example for interpolation or finite differences. The values of arrays that may be read between adjacent tiles are synchronized outside of the computational routines. Consequently, the values of a variable that was just updated may be used from an adjacent tile only in the next call to the computational subroutines, after the required synchronization was done outside. Synchronization within a patch is by exiting the OpenMP loop. Synchronization of the values between patches is by explicit HALO calls on the required variables and with the required width. HALOs are provided by the WRF infrastructure and specified in the registry.

The overall structure of the parallelism is spread over multiple software layers, subroutines and source files. The computation is organized in stages, controlled by the value of `ifun`.

```
! the code executes on a single patch
! if distributed memory, we are one of the MPI processes

do ifun=ifun_start,ifun_end ! what to do

  if(ifun.eq.1)then  ! this HALO needed before stage ifun=1
     #include "SOME_HALO.inc" ! communicate between patches
  endif
...
!$OMP PARALLEL DO
  do ij=1,num_tiles ! parallel loop over tiles

     if(ifun.eq.1)then   ! one of the initialization stages
  call         some_atmosphere_to_fire_interpolation(…)
 endif
 ...
     call sfire_model(…,ifun,…) ! call the actual model
     ! for some values of ifun, sfire_model may do nothing

     if(ifun.eq.6)then   ! fire step done
  call         some_fire_to_atmosphere_computation(…)
 endif

  enddo ! end parallel loop over tiles
  ! array variables are synchronized between tiles now

enddo ! end ifun loop
```

Software layers

The fire code is called from WRF file `dyn_em/module_first_rk_step_part1`. The output of the fire code (the heat and moisture tendencies) are stored on exit from the fire code and added to the tendencies in WRF later in a call to `update_phy_ten` from `dyn_em/module_first_rk_step_part2`
The fire code itself consists from the following files in the `phys` directory, each constituting a distinct software layer:

`module_fr_sfire_driver.F` **Fire driver** layer: Subroutines called directly from WRF. All parallelism is contained here. The rest of the code runs is called on a single tile.

`module_fr_sfire_atm.F` **Atmosphere-fire interaction** layer: routines to interface fire and the atmosphere, interpolate between fire and atmosphere.

`module_fr_sfire_model.F` **Fire model** layer: The fire model itself, callable independently of WRF. Calls the core and the physics layers. Formulated in terms of the fire grid only. Intended to be independent of particular mathematical methods used in the core layer.

`module_fr_sfire_core.F` **Core** layer: Numerical algorithms for fire propagation and fuel decay calculation. Dimensionless. Calls the physics layer for the fire spread rate.

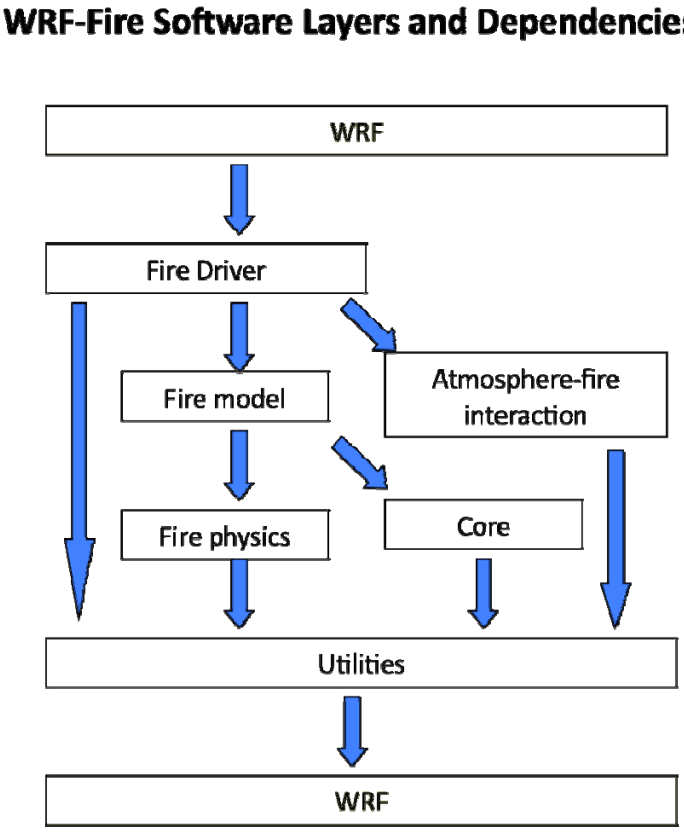
`module_fr_sfire_phys.F` **Fire physics** layer: Physical fire spread model and associated initialization.

`module_fr_sfire_util.F` **Utilities** layer: Used by all other layers. Declares scalar switches and parameters. Contains all interpolation and other service routines that may be general in nature and could be conceivably used for multiple purposes, and interface to WRF routines such as messages and error exits. To maintain independence on WRF, this is the only layer that may call any WRF routines.

`fr_sfire_params_args.h` Include file for subroutine argument lists to pass through all arguments that are needed in the fire spread rate routine in the physics layer. Necessary to write this long argument list only once given the WRF requirement that arrays may be passed as arguments only, and not shared globally, say, as pointers. Also, the include maintains the independence of the core layer on the physics layer and the independence of the fire code on WRF.

`fr_sfire_params_decl.h` Include file with the matching declarations.

The dependencies (allowed direction of subroutine and function calls) between the layers and WRF are in the following graph:



Initialization in idealized case

The initialization of model arrays in the idealized case is done in the file `dyn_em/module_initialize_fire.F`

This file was adapted from other initialization files in the same directory and extended to deal with fire model variables.

a. Vertically stretched grid

Because of the fine meshes used in fire modeling, the user may wish to search for the text `grid%znw(k)` and modify the following loop to assure a desired refinement of the vertical atmospheric grid near the Earth surface:

```
DO k=1, kde
     grid%znw(k) = (exp(-(k-1)/float(kde-1)/z_scale) &
     - exp(-1./z_scale))/(1.-exp(-1./z_scale)
ENDDO
```

b Topography

The relevant code is found by searching for the text

```
!******* set terrain height
```

The terrain height needs to be set consistently in the atmosphere model in the array `grid%ht` and in the fire model array `grid%zsf` at the finer resolution. In the supplied examples, controlled by namelist.input variables `fire_mountain_type`, `fire_mountain_start_x`, `fire_mountain_start_y`, `fire_mountain_end_x`, `fire_mountain_end_y`, and `fire_mountain_height`, both arrays are set consistently from an algebraic formula (a cosine hill or a cosine ridge).

It is possible, though not recommended, to set only `grid%ht` and have the fire module interpolate the terrain height from the atmosphere mesh by specifying `fire_topo_from_atm=1` in namelist.input. This will result in blocky terrain with discontinuous terrain gradients, which will affect fire spread patterns.

Note that in a real run, the user should leave `fire_topo_from_atm=0` and both terrain height arrays are set consistently at the best available resolution from the WPS.

The user should not modify the code immediately after the setting of the terrain height arrays, which initializes a number of atmosphere variables consistently with the terrain height.