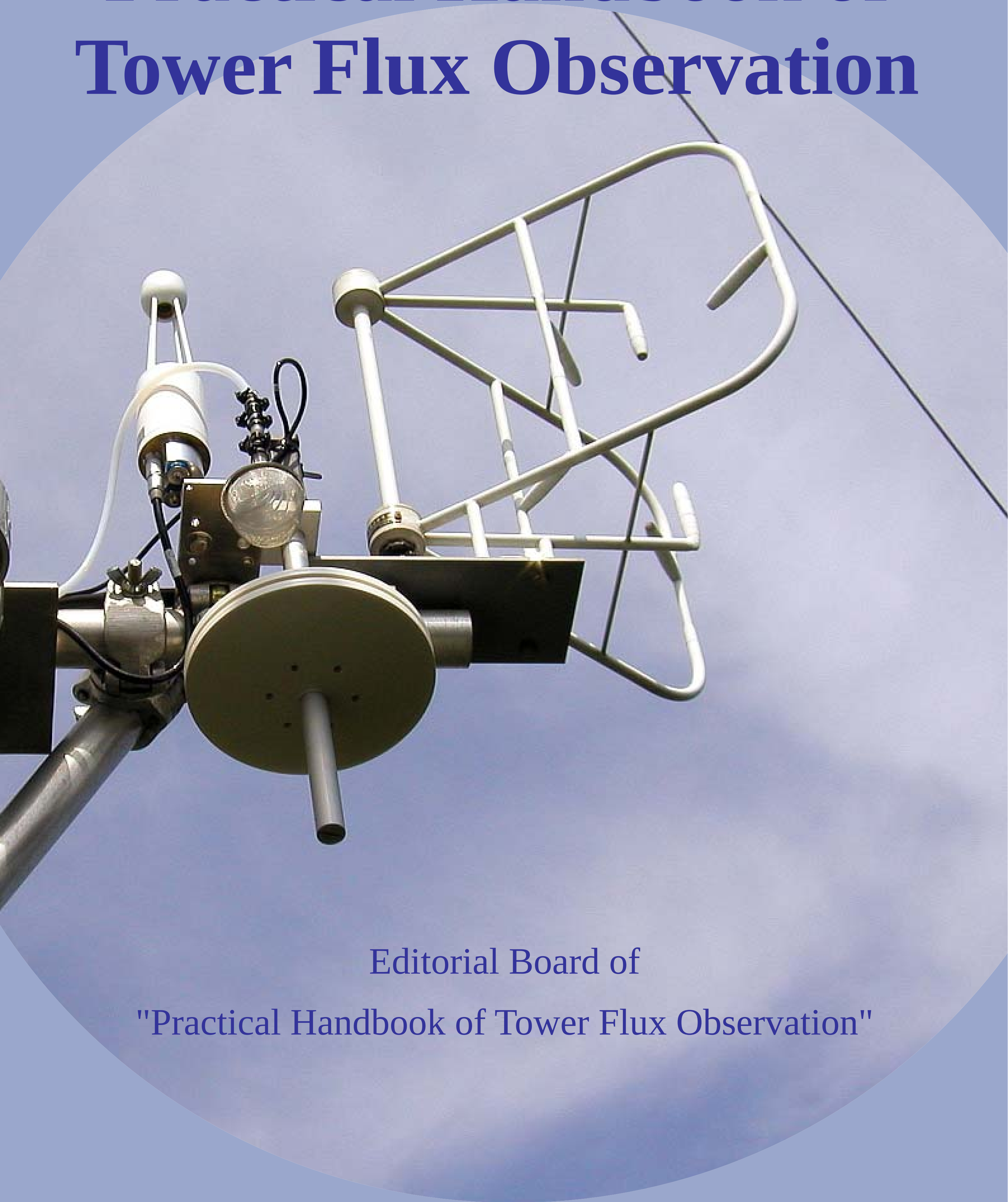
Practical Handbook of Tower Flux Observation



Editorial Board of

"Practical Handbook of Tower Flux Observation"

Editorial Board

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Preface

Efforts to mitigate global warming at the societal level call for a rapid implementation of systems that quantitatively evaluate the carbon dioxide (CO_2) budgets for forests, croplands, grasslands, and other terrestrial ecosystems. For observational studies of carbon budgets for terrestrial ecosystems, tower-based micrometeorological CO_2 flux observations conducted at the interface between the atmosphere and terrestrial ecosystems have attracted attention as an approach that allows direct measurements of the amount of CO_2 absorbed by the terrestrial ecosystems from the atmosphere. Such CO_2 flux observations have been taking place at more than 200 locations worldwide. Furthermore, efforts to integrate studies from tower-based observations on CO_2 and energy fluxes and those on the carbon dynamics and energy budgets of terrestrial ecosystems are currently in progress with the goals of improving the parameterization of ecosystem models relevant to global warming research and elucidating the influences of natural and anthropogenic disturbances, e.g., typhoons and land use changes, respectively, on the dynamics of diverse terrestrial ecosystems.

With this background, four research institutes (Forestry and Forest Products Research Institute, National Institute for Agro-Environmental Sciences, National Institute of Advanced Industrial Science and Technology, and National Institute for Environmental Studies) which have conducted long-term tower observations within Japan agreed to conduct joint research and development in 2007 in order to promote shared use of observation data, for which the reliability has been ensured and quality-control has been performed. The observation data under consideration concern exchanges of energy and mass such as CO_2 between terrestrial ecosystems and the atmosphere, the exchanges for which worldwide observation networking has been promoted. A micrometeorological observation and analysis technique called the eddy covariance method has become very common in recent years as a result of the development of measuring instruments with a relatively high response time and improvements in computational processing speed. This technique has enabled continuous acquisition of ecosystem production data as well as ecosystem-atmosphere mass and energy exchange (flux) data, without damaging the ecosystem under observation. Data acquisition with the eddy covariance method has, in turn, allowed clear evaluations of the diurnal, annual, and inter-annual variations of energy and mass (e.g., CO_2) exchanges, contributing significantly to improved understanding of ecosystem carbon dynamics and energy budgets.

Unlike general surface observations of meteorological variables, the micrometeorological technique does not require uniform conditions for the observation site and instrumentation. Therefore, while the micrometeorological technique offers various advantages, the data acquired with this technique have been subject to measurement uncertainties associated with variations in the observation location, observation method, and analysis method since the initial adoption of this technique. Currently, the observation-data sharing that has been promoted by FLUXNET, AsiaFlux and other related programs aims to inter-compare data through direct means or through indirect means such as model validation and also to achieve an improved understanding of the regional-scale carbon budget. Therefore, great care has been taken in order to eliminate data uncertainties including those associated with the use of the micrometeorological technique. For example, in Europe and Canada, instrumentation and analysis techniques have been standardized by creating manuals since the beginning of the observational efforts (Aubinet *et al.*, 2000; Fluxnet-Canada, 2003), and tower observations have been implemented in a systematic manner. In Japan, under the leadership of the AsiaFlux Steering Committee, "Current Practice of CO_2 and Other Flux Observations in Measurements for Terrestrial Ecosystems" (AsiaFlux Steering Committee (ed.), 2003 in Japanese, 2007 in English) was published, which has contributed to the improvement of observation and analysis standards and the establishment of an observation network by illustrating measurement and analysis techniques. In 2004, with FLUXNET as the nucleus of the project, a handbook with details on a wide variety of topics including the theory and technique of observation and analysis and examinations of factors affecting observation error was published (Lee *et al*. (ed.), 2004). With the manual and the handbook, a guideline has been created for handling factors which cause uncertainties in observation data. On the other hand, of the issues associated with uncertainties in observation data, errors induced by phenomena that depend heavily on the terrain conditions of the observation site, e.g., complex terrain, are fundamental causes of uncertainties in observation data and are rooted in the principle of measurements and analysis. This issue remains as a research topic which needs to be continuously addressed.

Accordingly, the number of literature references on observations by the eddy covariance method has increased compared to the time when such observations were initiated. However, when observations and analyses by the eddy covariance method are attempted in practice, detailed technical information that is not described in the existing publications becomes necessary for many of the tasks associated with the project such as starting a new observation site, deployment of the observation system, and analyses and quality control of the data. Given this circumstance, it has been proposed that data quality and distribution among researchers be increased by making the necessary technical information available on the internet and allowing researchers, who are aware of the necessity of standardizing the data, to share technical information. This proposal aims to contribute to the construction of a system that provides an improved estimate of the amount of CO_2 absorbed by terrestrial ecosystems, which is relevant in the mitigation of global warming. In the regions centered around Asia, tower-based observation sites within terrestrial ecosystems to be used for the purpose of validating various models remain scarce. Without detailed technical information such as that provided in this manual, it may be nearly impossible for a research team to start and operate a new observation site alone.

Because detailed technical information such as that described above is inseparably linked to the development of observation and analysis techniques, this information has been made available on the internet, which allows for relatively easy update of information – an advantage of the internet. Because the information included in this manual is published on paper at this time, the inability to easily update the information is one of the biggest concerns. Nonetheless, publication of the present manual is valuable in that it provides a record of the current state of observations and analyses from a technical point of view. It is our hope that the present manual will serve in transferring various techniques to the science communities in Asia and contribute to the efforts to mitigate global warming through the expansion of tower observation

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Preface to English edition

A half century ago, Dr. Eiichi Inoue, a pioneering scientist of turbulence in the atmospheric boundary layer and famous for his studies on “Honami” (waving plants), tried to measure carbon dioxide (CO_2) fluxes over crop fields by applying the aerodynamic method. He dreamed that a sensor similar to a heat flux plate could be developed in the future (he named the sensor the CO_2 flux plate), and that by merely setting the plate horizontally we could easily measure the CO_2 flux from the difference between the concentration of CO_2 at the upper side of the plate and that at the lower side of the plate. We may say that his dream “partially” came true with the development of the eddy covariance system consisting of a sonic anemometer, a fast-response infrared gas analyzer, and a data logger. Now, the eddy covariance system is used for monitoring fluxes of CO_2 as well as those of water vapor and sensible heat in various terrestrial ecosystems throughout the world.

However, the measurement of CO_2 flux using the eddy covariance system is not as easy as, and actually far different from that using the CO_2 flux plate which Dr. Inoue dreamed of a half century ago. It is certain that open- and closed-path infrared gas analyzers as well as sonic anemometers and data loggers have recently been much improved and have become more sophisticated so that we can operate those advanced instruments more easily than two decades ago. In addition, as the number of users of the eddy covariance system increases, manufactures and their agents are providing detailed instruction manuals, technical notes, and even training courses. However, these resources are not enough for someone who is going to start flux observations using the eddy covariance system because these materials and activities generally focus on how to use the individual instruments or the eddy covariance system at best, but do not discuss practical issues related to eddy covariance flux observation such as constructing an observation site including a tower and related facilities, setting up the eddy covariance instruments in the field, and conducting the micrometeorological observations that are inseparable from the eddy covariance flux observations. AsiaFlux has also had several training courses including lectures on the theory of flux observation, but could not spend much time on the above-mentioned practical issues, which are really required for newcomers, especially those without expertise in micrometeorology.

As shown by its title, the “Practical Handbook of Tower Flux Observation” focuses on the practical issues in eddy covariance flux observation and includes a substantial amount of useful knowhow and unique sections such as “lightning surge countermeasures” and “detection and reduction of noise”, which are rarely found in similar publications. All of the authors of this handbook have been engaged in long-term flux monitoring in forest or cropland sites and have expertise in eddy covariance flux observation. I sincerely appreciate the efforts of the authors to spend their valuable time to share their experiences and knowhow with the readers, and expect this handbook to be utilized as a practical reference by eddy covariance users and in training courses on eddy covariance flux observation. It is also my hope that another practical handbook, which focuses on the processing of eddy covariance data and is complementary to the present handbook, will be published in the near future.

August 2011

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Contents

1

Observation Planning and the Selection of Flux Observation Sites

1.1 The observation site

This section describes how to select appropriate sites for performing long-term, continuous observations of energy and CO_2 fluxes.

Basic concept

When selecting a site, you must clarify the purpose of your proposed observation by answering the question: In what type of ecosystems will these flux measurements be taken? Specifically, you must determine the following required conditions beforehand: vegetation type (dominant species), density, height, and age; climatic conditions; soil characteristics; potential disruptions in the ecosystem due to natural causes; and potential disruptions in the ecosystem because of man-made changes such as tree trimming or land development. Then, search for an appropriate observation site based on these variables. Careful site selection is important as it can profoundly affect the validity of your observational data; preliminary studies on possible observation sites are worthwhile.

Flux measurements performed using the eddy covariance method postulate fewer atmospheric or land-surface condition as compared to those performed using other micrometeorological methods. However, the eddy covariance method does require that there is a flat terrain and homogeneous vegetation in the windward side of the observation point (Schmid, 1997).

Preparation

Select candidate observation sites based on information collected from the following: topographic maps, vegetation maps, aerial photography, satellite images, land use maps, forest management maps, data on climate and hydrological conditions, and history of land use and management. With respect to climatic conditions, studying the speed and direction of prevailing winds and changes in their daily and seasonal patterns helps to determine the most appropriate site for flux measurements and sensor positioning. Practically, it is necessary to collect information on land ownership, land-use rights, and building restrictions. It is also important to find out the social structure and security of the area from people who are familiar with the surrounding region. At the same time, draw up an observation plan that specifies the observation period, methods for managing vegetation, manpower requirement, methods employed for data collection, data usage, and procedures for making the data publically available, as well as any relation between your study and other flux observation studies.

Tips!

Flux measurement studies require two full-time staff members for each observation site (Baldocchi *et al.*, 1996). Additional staff members are required for the measurement of other items such as micrometeorological variables. Advances in measurement equipment have reduced the need of maintenance, and thus number of staff. Even then, it is better to avoid working alone in high places on a tower.

Tips 1.1-1

Selecting a flux measurement point

When candidate sites have been identified, you should reconnoiter them, and if possible, view them from above. Select an appropriate observation point (to set up a tower or pole) and ensure that there is a vast expanse of flat terrain and homogeneous vegetation on its windward side. It is desirable to set the flux measurement height at least twice as the vegetation height. However, due to technical limitations and micrometeological-footprint restrictions (see section that contributes to the observed flux: 1.2.2, “Tower construction and maintenance”), the height of the flux measurement might be lowered in some instances.

Avoid areas that have artificial facilities, such as buildings and power transmission lines or areas that have cars and other traffic facilities nearby. This is because gas emissions from traffic and electrical noise can invalidate your observational data. It is ideal to have an areal allowance of the same ecosystem for conducting ecological and pedological surveys, which would disturb vegetation and soil but without affecting flux observation. In most of the Asian countries, it is not rare that agricultural areas other than permanent grasslands are managed in sections of one hectare or less. Each section may use a different management method, and this can have an adverse effect on the observation results. It is important to take this factor into consideration when conducting a preliminary survey on an observation site.

Access

It is desirable that there is a road leading to the observation tower so that heavy equipment can be carried into the tower for maintenance. Where there is no road, one should be built, or if it is difficult to build a road because of strict restrictions on the use of roads or due to steep slopes, installing a monorail is a good option. However, since emissions from vehicles can adversely affect observation results, it is necessary to have some restrictions on traffic.

Remote site

There are some areas that are difficult for people to access, but they must be observed as they are considered important ecosystems. We call an observation site installed in such an area as a “remote site”. What steps must be taken to conduct a long-term survey at such remote sites? It is impossible to install commercial power lines in such locations. Access is also extremely inconvenient. To enable observational studies in such an area, we should first plan how to address problems with the living environment, such as problems relating to transportation and accommodation.

Obtaining the cooperation of local residents is also essential for conducting a successful study. Prior preparation is ideal as it ensures that many obstacles are removed before the study begins. Continuous year-round observation is ideal in principle, in many cases however, that is not always possible due to limited budgets, human resources and electric power supply. In such case, we should reduce the number of observation items and the duration of observation to secure the indispensable data. Moreover, it is desirable to set up an additional weather station in a readily accessible location where security and electric power for collecting supportive meteorological data throughout the year (Photo 1.1-1).

Photo 1.1-1 A supportive year-round weather station. (Tura, Russia)

1.2 Building infrastructure

This section describes some public procedures of the government, with cases of Japan as examples. When setting up an observation station in other countries, it is necessary to proceed corresponding each local or national government.

1.2.1 Obtaining permission for land use (example of case in Japan)

Private land

It is difficult to provide a general explanation of the procedures involved in acquiring permissions for land-use for studies that include the construction of towers or roads on private land. It is necessary to discuss the procedures with the land owners, and also, be sincere and patient in all your dealings with them. While proceeding with the procedures for acquiring permission for land use, you should begin the necessary construction and survey work. If the observation site is situated in an area designated as a national park, a protected forest, or an erosion control area, then you need to obtain permission from the proper authorities to use the land. (Details are explained below.)

Agricultural land

When you set up an observation station on an agricultural land, you must first obtain permission from the land owner to use his land for the study. Towers tend to be rather small when built on agricultural lands, compared to these in forest, and the impact of tower and facilities on cultivation should not come to an issue. However, constructing objects such as towers in the middle of fields can adversely affect the efficiency of agricultural work (especially work done by tractors and machinery). When negotiating the rent with the land owner, this point should be taken into consideration.

Although installing a tower in an agricultural field rarely affects the surrounding fields, the consent of neighboring land owners must also be acquired for managing the observation site. The consent can be acquired through a land improvement organization or other local organizations. It is always important to maintain amicable relation with neighboring land owners as they might also provide information that is useful for your study.

Special areas and specially preserved areas in national parks and quasi-national parks

When you set up an observation station in special areas and in specially preserved areas of national parks or quasi-national parks, you need to obtain permission from the proper authorities. For a national park, obtain permission from the Environment Minister; for a quasi-national park, obtain permission from the Prefectural Governor (Articles 13 and 14 of *The National Parks Act*). The installation of facilities is strictly regulated in these areas, and it is therefore, difficult to build a tower larger than the simple one such as shown in Photo 1.1-1.

National and public forests

When the observation tower or roads used to access the research site are part of a national forest, you need to obtain a Permit for Using National Forest for entering the forest. First, visit the local forest management office and forest administrative bureau for applying to obtain permission to use the forest and start negotiating with them sincerely. For land use activities that entail observations to be made as part of a public research project, you can collaborate with public research organizations by following the procedures outlined in the Implementation Guideline for Technical Development of Forest Office and in this case no land use fee will be charged. Instead you will be obliged to submit annual reports on the implementation of technical development. With regard to the use of forests owned by prefectural governments and other municipalities, the process of obtaining permission varies from community to community. Some local governments have systems that allow for land lease and prefectural forest use. Contact the division in charge of forests and follow the necessary procedures. If the target forest is designated as a protected forest or an erosion control area, then you need to acquire a protected forest work permit or an erosion control work permit just as you would have done for the use of private land.

Protected forests

When large-scale construction and other work are to be performed in a protected forest area, you can file a petition for the designation of the protected forest to be cancelled. To apply for such cancellation, either of the following two conditions is required: when no reason can be found for the forest to be designated as a protected area, or; when the outcome of research will be significant in terms of public benefit, and will be more important than the protection of the forest. In reality, however, there is only a slight chance that any such application will be accepted, even if it meets the requirements outlined above. So, when you undertake a small-scale observational study in a protected forest, you need to apply for a permit, register the observation tower and cabin as temporary buildings, and obtain a permit to cut down a few trees (a protected forest work permit).

Erosion control area

The need for observations is not among the reasons for the designation of an erosion control area to be cancelled. It is also virtually impossible to build permanent buildings in a location that is designated as an erosion control area. This also applies to rivers. Building facilities or roads in an area that has been designated as an erosion control area under *The Sand Control Act* or alongside rivers that have been defined as rivers by *The River Act* is extremely difficult. However, it is possible to obtain permission to construct a few temporary buildings in these areas not by obtaining a Construction Permit, but by obtaining an Action Permit in an Erosion Control Area and River.

Tips!

To renovate a boardwalk or an observation station located in a protected forest or in an erosion control area, you must apply for the permits stated above each time. Please remember this when you plan to make large-scale repairs.

Tips 1.2-1

Tips!

Although an observation facility is usually temporary, *The Building Standards Law* requires you to obtain a construction certificate if you intend to use it for a long time period. Besides obtaining land-use permissions, confirm whether you need to obtain a permit for building a tower and an observation house and if required, follow the necessary steps for obtaining these permits.

Tips 1.2-2

1.2.2 Tower construction and maintenance

Height

The specifications of a tower for flux observations between the atmosphere and ecosystem in forests, grasslands, or agricultural lands are determined by the construction budget and on-site conditions however, the tower must be at least higher than the surrounding vegetation. There have been cases (e.g., Laubach *et al*., 1994) where measurements taken from observation points that were 3 % higher than the surrounding vegetation were not very different from those taken from observation points that were 50 ~ 70 % higher than the surrounding vegetation. Thus, observations are possible at any height provided the observation site is slightly higher than the surrounding vegetation. However, measurements taken at a lower site tend to be influenced more strongly by the surrounding vegetation. So, it is necessary to check whether the observed values are representative of those of the surrounding vegetation. Footprint analysis prior to observation is an efficient means of verification (e.g., Schuepp *et al*., 1990; Rannik *et al*., 2000; Kormann and Meixner, 2001; Okada, 2002). However, along with such ex ante analysis, it is recommended that site inspections be performed at various observation heights (depending on on-site conditions). In such cases, the tower must be higher than the surrounding vegetation with a certain allowance. Also, if long-term observations are performed at a height close to the vegetation height, then the vegetation will grow and approach the measurement level. Therefore, when a tower is constructed, its height should at least be 1.5 ~ 2 times that of the surrounding vegetation, regardless of the height of the flux observation equipment.

Tower types and features

In grassland or agricultural areas, a pole-like tower of approximately 3 ~ 5 m is used in most cases

(Photo 1.2-1). There is a free-standing type of tower, which has a pipe driven deep into the ground; a reinforced type that is supported by wires; and a tripod type.

Photo 1.2-1 A pole-like tower. (Mase paddy flux site)

In a forest, a higher tower is needed. Most common type is the one which the observer can climbs up with the instruments. Some of the towers have stairs (Photo 1.2-2; here we call it a “scaffolding tower”) and others have ladders (Photo 1.2-3; here we call it a “ladder tower”). There is also another tower type with an elevating table attached to lift up the instruments to the top.

The advantage of using a scaffolding tower is that it is easy to ensure the safety of the climber. It is also easier to go up and down the stairs when holding an instrument in hand. So the installation and maintenance of instruments is comparatively easy, even when there are few observers.

In case of a scaffolding tower, a four-sided tower is built on a comparatively broad yet shallow foundation, with metal stays that extend outward from the four corners of the tower and are fixed to the buried concrete anchor. An anchor is important for ensuring adequate protection against strong winds, so sometimes a large anchor is buried deep in the ground (e.g., an anchor of more than 1 m^3 is buried at a depth of more than 1 m). In snowy areas, where snow load such as weight on the metal stays and settling force can be significant, a scaffolding tower without stays is possibly chosen. In such cases, it is necessary to have a large base area and to use reinforcing materials that are selected on the basis of their strength to withstand the snow season.

A scaffolding tower that uses ordinary scaffolding pipes and clamps is treated as a temporary construction at a general construction site, whereas a tower used for long-term observation must have an appropriate distribution of stiffened elements, based on specifications such as the tower height, and it should be designed and constructed using strength calculations based on the planned height of the tower and properties of the construction materials. From the perspective of construction and maintenance, using strong, lightweight materials (such as aluminum) is preferable, but the material costs rise steeply.

Many ladder towers consist of triangles (or quadrilaterals) of about 10 cm on one side (Photo 1.2-3). These towers are used for radio and cell phone communications, and materials and strength calculations are often set as standards. Since telecommunication towers are used around the world, it is easy, even in overseas, to construct such a tower as it can be built relatively cheaply according to the local labor costs. It is also possible to add an optional electric or manually operated winch or space for working and evacuation, which is called a safety box or stage. However, this type of tower requires greater physical strength of the observer for moving up and down the tower compared with the scaffolding tower. Also, when working at great heights, the sensation of being high above the ground is more intense, and this will limit the number of people who can work in such an area. It is also difficult to move up and down while holding something, so to set up an instrument you need a pulley and a rope as well as a support person on the ground. A device for preventing falls when working high above the ground or safety gear used for mountain climbing is indispensable for moving up and down this type of tower. Moreover, setting up metal frames that are used for climbing greatly reduces the worker's sense of fear when installing and removing safety appliances. This type of tower stands like a rod on a base, whose area is relatively small with respect to its height. So, when it is used for long-term observations its foundation should be laid very deep in order to prevent it from falling over. Also, it is possible to build this type of tower, depending on the height, as a self-standing tower without the use of stays. However, when the height of the tower greatly exceeds the top of the forest canopy, metal stays and an anchor of appropriate size are required.

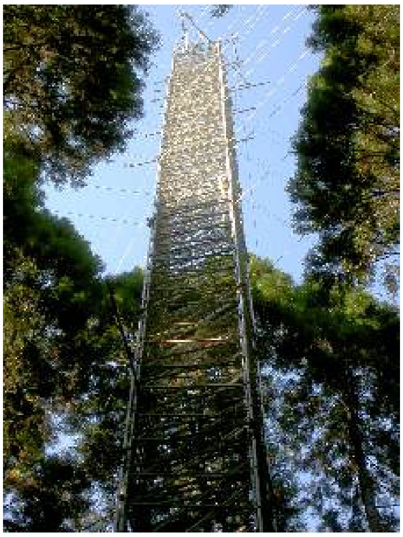

Photo 1.2-2 "Scaffolding tower" with access stairs. (Kahoku Experimental Watershed)

Photo 1.2-3 "Ladder tower" with a ladder-like part for easy access. (Kampong Thom Province, Cambodia. Photograph: courtesy of Shimizu Akira)

Photo 1.2-4 Monorail used for transporting construction materials.
(Yamashiro forest hydrology research site)

Transporting construction materials

Since usually a high tower is constructed in a forest and most of the construction work is done in the mountains, the transport of construction materials is arduous. Use a monorail to effectively transport materials in large amounts while minimizing damage to the forest floor (Photo 1.2-4). The price of a monorail car is about three million yen, and the costs of laying the rail is about 30 ~ 40 thousand yen per meter.

Tower maintenance

Maintenance of an observation tower is essential to ensure that observers working at the tower are safe. If a tower is constructed with a strong foundation, using materials that have been chosen based on suitable calculations of their strength, it can last for more than ten years unless damaged by a natural disaster. However, even when it does not experience strong winds or a severe earthquake, the tension in the stays of a tower will change slightly because of vibrations caused by wind and the observer's movements on the tower. It is thus preferable to measure the tension of the stays once a year, using a tension meter, and to adjust the tension based on these measurements. It is also necessary to constantly check for corrosion of the metal joints on the tower and to replace them when necessary by ordering the parts from a supplier or by contacting the tower builders.

Especially for a tower built in a forest, even if the tower itself is designed to sustain vibrations induced by strong winds, it is conceivable that a tree could fall on the tower or on the stays and cause severe damage. To prevent this, any tree that could potentially interfere with the tower or the stays should be cut down. In a forest with a fully closed canopy, cutting down a single tree creates a gap in the forest, but the influence on the observational results appear to be small (e.g., Kelliher *et al.*, 1995). If many trees need to be felled, there are concerns that labor for cutting and transporting them will be considerable and that the habitat will change. Instead of cutting trees, it is recommended that the target trees be tied to other trees with a steel wire (Photo 1.2-5). Trees that are tied together do not fall as easily as single trees and the risk of their causing damage to the tower or to the stays is also much lower. The Kahoku Experimental Watershed of the Forestry and Forest Products Research Institute was hit twice by typhoons with

Photo 1.2-5 Trees connected by steel wires at the base (left) and at 10 m (right). The red arrows show the connections. (Kahoku Experimental Watershed)

maximum wind velocities of 50 ms^{-1}, but none of the trees that had been tied together fell and so there was no damage to the tower or the stays and the observations can be continued without interruption.

At an observation site located on an agricultural land, agricultural work such as crop planting, harvesting, and cultivation is conducted (mostly by machines) several times in a year. These alter the ground surface conditions. A tower built on an agricultural field can interfere with agricultural work, but observations of upward radiation, soil heat flux, plant community profile, and so on are often carried out in the vicinity of the tower, so it is important to ensure the homogeneity of the land, even in the vicinity of the tower. There are two ways to do this: One is to carry out observations by setting up a simplified tower that can be easily transported (such as a tripod) and pulling down the tower temporarily when there is agricultural work to be done; the other is to carry out observations at the permanently installed tower after asking the field administrator to avoid agricultural work around the tower and having the observers themselves do the agricultural work manually in the vicinity of the tower. Even when the latter option is chosen, it is better to pull down the tower once in several years to ensure cultivation of the entire agricultural field.

1.2.3 Electric power supply

Commercial power supply

Wherever possible, the use of a commercial power supply is recommended as is the introduction of a facility that has considerable capacitance. A back-up power supply should be maintained for the event of power loss, and the observation system should have automatic data saving and power restoration features.

To install a commercial power supply at the newly set-up experimental site, certain steps have to be followed by an electrical contractor who is affiliated with the power company based in each region. For example, Kandenko Co., Ltd in the region around Tokyo. Locally registered electricians can be recruited through the local office of the power company in each region. If there are residential area close to where power is to be installed, setting up the power supply can be done free of charge for a certain distance from such area. When a meteorological observation tower is installed, it is often several kilometers away from the residential area, there will be indispensable expenses for its installation, including the installation of electric poles and electric wires. Rental expenses will accrue when electric poles are present on private land.

Tips!

Comprehensive discussions with personnels of an electrical engineering company affiliated with a power company can greatly improve their support level. It is important to emphasize the public nature of observations, taking the time and making the effort to provide an explanation for your activities and to participate in negotiations on-site prior to beginning your study.

Tips 1.2-3

When installing a power supply line, high voltage electric power lines should be laid as close as possible to the observation tower or to the experimental site in the forest, and a transformer should be set on the nearest electric pole. This avoids problems such as power line noise after the start of the observation, and it also makes it easy to change the capacitance.

As for wiring in a forest, in order to prevent the wire from being cut or damaged by falling trees, the power supply line should be laid on or under the ground after being placed into protective tubes. (Products such as corrugated pipe, accordion pipe, and so on can be used.) If a power supply line is laid under the ground, then maintenance after setup is difficult. It requires efforts such as setting up a linkage box midway along the line. As for wiring on telephone poles, it may be necessary to cut down some trees so that they do not touch wires (Photo 1.2-6). When conservation of the forest is a priority, it is better to install the power supply line on or under the ground. When the situation allows, “unfixed wiring” on the ground, using protective tubes, is favorable for maintenance (Photo 1.2-7).

When the location is isolated and a commercial power supply is unavailable, a dynamo or a power generation system employing solar panels can be used. Nowadays, many observation sites use a photovoltaic generator based on solar panels. When a dynamo is used, it should be installed in such a position that its exhausts do not affect flux observations.

Photo 1.2-6 Aerial wiring in a forest. (Yamashiro forest hydrology research site)

Photo 1.2-7 Unfixed wiring. The forest floor undulates, so it is more practical to use underground corrugated protective tubes for unfixed wiring. (Yamashiro forest hydrology research site)

Tips!

When a high voltage electrical power line cannot be extended to the transformer of the utility pole near the observation facility, long-distance power transmission is needed between the transformer and the observation facility either with an AC 100 V line or with a 200 V single-phase three-wire system. In this case, the resistance of the wire extending to the observation facility can cause a voltage drop. As a result, depending on the electric power required, sufficient power-supply voltage may not be available for conducting observations. Use of a wire with small conductor resistance (i.e., a thick wire) helps to minimize the voltage drop. Many measuring instruments that operate normally at 95 V perform unstably at 90 V though the degree of instability depends on the individual measuring instrument. Therefore, the voltage of the AC power supply that is to be used for the observation system needs to be checked.

Tips 1.2-4

Electric power generated by a photovoltaic power source

Photovoltaic cells on solar panels charge batteries using sunlight. During sunshine hours, a photovoltaic generator generates more power than what the observation system needs, and the surplus is used to charge the battery. The charged power is consumed during the night or during non-sunshine hours. A charge controller is used to prevent the battery from overcharging and also prevents excessive discharge. In terms of the charging capacity and durability of the battery, it is most appropriate to use a deep cycle battery as it can be used even when fully charged, and it also delivers a consistent voltage as it discharge. The capacity of the solar panel and the battery depend on power consumption by the observation system and on the amount of available solar radiation. For more information on how to calculate capacity, please refer to the technical data posted on related websites. The available electric power is limited. The observation system should have low power consumption itself, and equipped with automatic power control functions including saving of on-memory data, turning off low-priority devices for power saving, and restarting of observation.

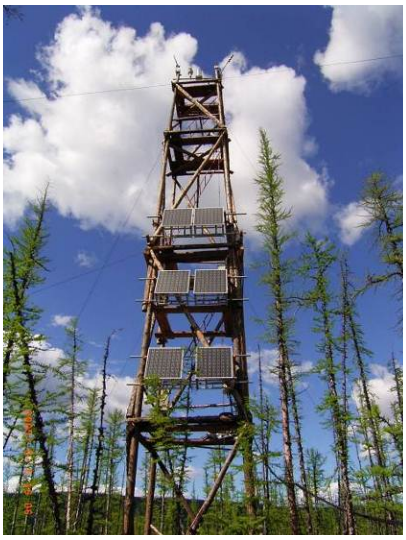

Photo 1.2-8 A flux observation tower using solar cells. (Tura, Russia)

The main precautions to take when using solar panels are as follows: 1) solar panels should be used so that the wind impact on the flux sensors is minimized; 2) the wind resistance of the panel is high, so care should be taken that the tower or the panel is not blown away by the wind; 3) the electrical resistance of wiring should be small and loss of power should be minimized; and 4) care should be taken to avoid electric shocks caused by the electric current in the panel. Measures such as light shielding should be taken when work is performed in the vicinity of the panels. An example of a flux observation tower using solar cells is shown in Photo 1.2-8.

Tips!

When a lead storage battery becomes overly discharged, the precipitated lead sulfate forms hard crystals on anode of the battery. This is called sulfation, and these crystals have a low solubility, which makes it practically impossible to recharge the battery. Deep-cycle batteries are the same, because they are lead storage batteries in principal. However, their electrode are strengthened to make them more discharge resistant than ordinary lead storage batteries.

Tips 1.2-5

Tips!

Solar panels should be set up to achieve the maximum possible production of electricity. Sun's rays should preferably hit the panels at a right angle, but since the sun's angle changes daily and seasonally, solar panels are usually set at an angle of 10 ~ 40 degrees facing south (north in south hemisphere). The influence of surrounding obstacles on the panels is taken into account as well as the influence of the panels themselves on flux observations.

Tips 1.2-6

1.2.4 Lightning surge countermeasures

Lightning damage on tower observations

Since lightning tends to strike tall, pointed objects, observation towers are prone to lightning strikes. Electric current (lightning surge) generated by lightning momentarily produces a large current and a high voltage, and these can damage observation facilities. There are two kinds of surges: a direct lightning surge caused by direct strikes on a tower; and a lightning-induced surge caused by strikes on the surrounding area. Both cause damage that can include destruction and breakdown of electronic observation equipment. Surges caused by direct lightning strikes generate a particularly large amount of energy and they can cause severe damage, including fires.

For flux observation facilities, installation of lightning protection equipment is required by law when the facility is first established and additional measures can also be taken to ensure the protection and safety of observation equipments. The former includes installing a lightning rod on an observation tower, and the latter includes protecting power lines, communication lines, and sensor signal lines.

Lightning rod

Installing a lightning rod is the most effective protection against direct lightning strikes. An observation tower more than 20 m high is required to have a lightning protection system (lightning rod) according to Article 88 of *The Building Standards Act*. A lightning rod can be installed by the builder during tower construction (Photo 1.2-9) and at the same time a ground with little earth resistance (< 10 Ω) should also be installed (Fig. 1.2-1).

Even if lightning strikes the lightning rod, surge current can be produced by electromagnetic induction in various cables wired to the observation facility and this can damage the observation equipment. Thus, surge arresters are required even if a lightning rod is installed.

Photo 1.2-9 A lightning rod (left) and a ground (right) installed in an observation tower.
(Sapporo forest meteorology research site)

Surge arrester

Abnormal current flow induced by a lightning surge can damage observation equipments by various routes (such as via electric power lines, communication lines, and sensor signal lines). A surge protection device (SPD) or a surge arrester should be installed between the observation equipment and any line that is wired to the observation hut.

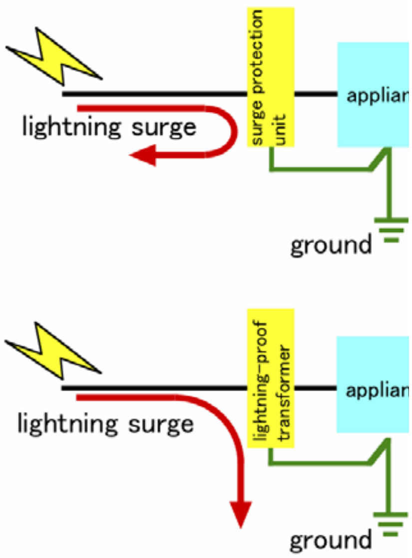

Fig. 1.2-1 Comparison of lightning-proof transformers and SPDs.

Countermeasures for power lines

Lightning-proof transformers or SPDs in power circuits are used as surge protectors for power lines, as shown in Fig. 1.2-1. SPDs in power circuits are smaller and cheaper than lightning-proof transformers; thus, they are easier to install in a temporary facility such as an observation hut. To discharge surge current to the earth through the ground, it is necessary to prepare a good ground that has little earth resistance. Preliminary discussion with builders is necessary as these protective devices should be installed at the same time when the power lines are laid. Plug-in appliances called surge protectors are commercially available, and some of these are built into power strips or uninterruptible power supplies and are easy to use.

Countermeasures for communication lines

For communication lines, SPD is selected according to the type of line used. As with power lines, these are installed during line installation, and plug-in appliances can be used. Damage to the network can be reduced by using optical lines.

Countermeasures for sensor signal lines

Sensor signal lines installed in a tower can also serve as discharge paths for surge current. A large number of measuring instruments are set up in observation towers, so using terminal blocks for these instruments (Photo 1.2-10) makes it easier to perform lightning surge countermeasures. All signal lines should be grounded to protect the observation equipment, with protective elements such as ceramic surge arresters or varisters. The connecting location and the surge path are the same as those for SPD in a power circuit (Fig. 1.2-2). Ceramic arresters are small and well suited for connection to the terminal block. The terminal block should be connected to a ground that has little earth resistance.

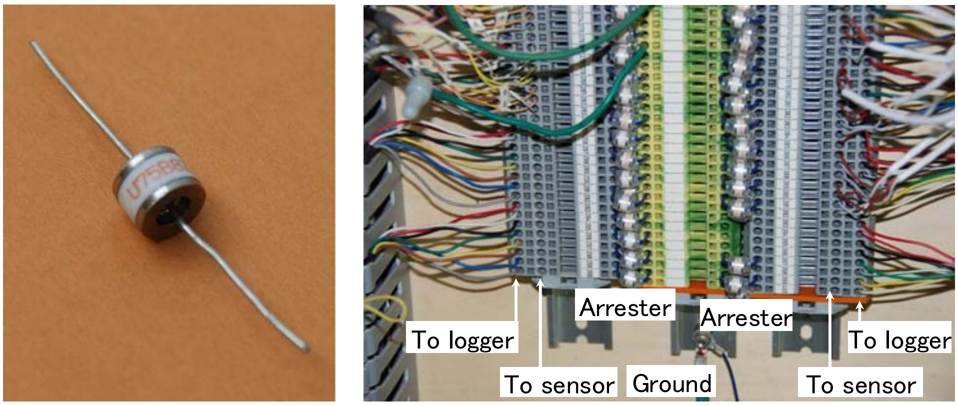

Photo 1.2-10 Ceramic arrester (left) and arresters connecting the terminal block (right).

Installation of the ground bar

A ground bar should be installed as a countermeasure against noise and lightning surges that may damage signal lines and electric power supply. These grounds should be separate from the lightning rod ground (Photo 1.2-9). The ground for electric power supply is installed when the source facility is constructed. As shown in Photo 1.2-10, a ground is needed when countermeasures are taken against surges in signal lines. A ground that is installed for such a purpose should have a ground resistance of 100 Ω or less. In an area of ordinary geology, simply inserting a 50 ~ 100 cm ground bar into the earth (Photo 1.2-11) is enough to keep the resistance within 100 Ω. The ground bar should be inserted into a soil that is as moist as possible, and the tip of the bar should be at a depth of 40cm or more. Argilliferous soil is preferable. Sometimes it is difficult for a ground to work effectively in gravelly soil, in such a situation, ground bars should be buried 2 m apart and wired in parallel. It is also preferable to wire the ground with electrical cables that are as close as possible to the grounds of the connected device.

Photo 1.2-11 Ground bar.

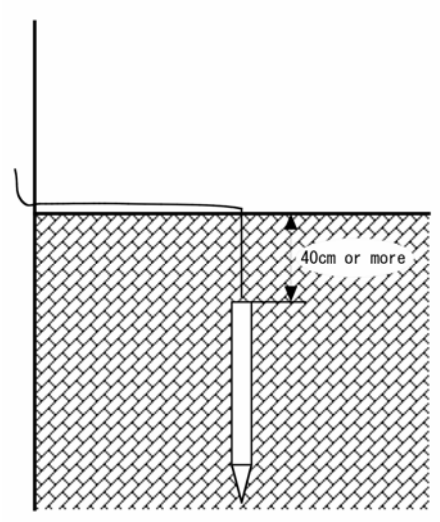

Fig. 1.2-2 Installing the ground bar.

Other matters

The most effective lightning countermeasures are cutting off the equipment power and unplugging the power and communications cables. Instantaneous failure of a power line can occur during a lightning storm, and an operational check of the observation equipment should be performed once it is safe to do so. It is also very important to avoid working at or near a high tower when lightning strikes are likely.

Tips!

Telecommunication appliances, such as telephones, modems, and computers connected to the two types of electric lines (power cables and telecommunications lines) are the items most likely to be damaged by lightning. This is because of electrical surges that enter one line and exit by passing through another such appliances. This can occur in electrical as well as ground lines. Therefore, it is best to avoid addition of unnecessary electrical lines.

Tips 1.2-7

Tips!

There is often little space for connecting protective elements, such as ceramic arresters, to a terminal block. To prevent these elements from touching, they should be protected with heat-shrink tubing or insulating tubing (Photo 1.2-10).

Tips 1.2-8

1.2.5 Observation hut

Flux observations often require an observation hut where computers and data loggers can be stored. The hut should be as small as possible so as not to disturb the observation environment. Building the hut close to the tower will shorten the length of plumbs and wires and will be conducive for operation, but the hut must be placed at a distance that ensures it does not impact the observation environment. A simple heating, ventilating, or air-conditioning facility may be needed, depending on the climatic conditions. It is better for the floor of the hut to be above the ground level. This makes it more difficult for soil and sand to be brought into the hut, and it also makes it easier for you to keep the inside of the hut clean. For a hut used for storing gas cylinders for calibration of CO_2 concentration, it is more convenient to bring the cylinders into the hut when the hut is built near a road. It is also a good idea to set up two huts, one for storing gas cylinders and the other for storing data loggers and other measuring instruments. When the latter hut is close to the tower, it has the advantage of requiring shorter wires.

The Forestry and Forest Products Research Institute uses commercially available tool sheds placed on a concrete foundation (Photo 1.2-12). The floor has to be adequately strong to store heavy items such as gas cylinders. For this reason, concrete or other sturdy materials are used. Steel transportation containers are used as a observation hut in countries where security is poor.

Many of the present observation sites of the Forestry and Forest Products Research Institute have huts just beneath the tower, the reason being that such an installation has little effect on the tower. This is particularly true in Japan, where the forest canopy tends to be dense. In contrast, observations near the ground level in a forest should be performed far from the hut or tower. When an observation hut is set up on an agricultural land, on grassland, or in an open forest with little vegetation, it needs to be far from the tower. When minimal amounts of data are to be collected, it may be possible to avoid installing a hut at all in which case data loggers, control loggers, control equipment, and measuring instruments can each be stored in separate measuring boxes.

Photo 1.2-12 An observation hut close to the tower (center), and a shed for gas cylinders (right). (Sapporo forest meteorology research site)

Photo 1.2-13 A measuring box with desiccant (closet dehumidifier) inside.

Tips!

Measurement boxes should be sealed as tightly as possible to keep out rain, insects, and humidity. Holes for wires should be filled in with clay putty, and the desiccant in the box should be replaced regularly. A closet dehumidifier can also be used, if there is enough space in the box (Photo 1.2-13).

Tips 1.2-9

1.2.6 Other

Paths

For the conservation of vegetation and soil, paths should be established for routes that are frequently used by people, such as paths between the hut and the tower, from the parking area to the hut or tower, and for approaches to observation equipment installed on the ground. Paths are indispensable in wetlands or rice paddies, where a boardwalk is often installed (Photo 1.2-14). Careful consideration of factors, such as whether a boardwalk is required or not, is also needed in a forest site to ensure conservation of soil and vegetation around the tower over the course of time.

An important point to remember while maintaining facilities on an agricultural land is to avoid losing tools and metal fittings (clamps, bolts, nuts, arms, piles) that are used for fixing and supporting the tower and for measuring appliances and cables in the fields. Lost items such as these can hinder agricultural work, damage agricultural machinery, and possibly, injure workers. Even in an area where a rental fee is paid, disruption to crops and soil should be minimized. It is not pleasant for a landowner or manager to have his land damaged, even if compensation is provided. Long-term observational studies on a private land require such careful consideration.

Photo 1.2-14 Boardwalk installed around tower. (Tura, Russia)

Fences and security

A high tower should be fenced off from the surrounding area so that people cannot freely access the tower as there is a possibility that a person under the tower could be injured by a falling object. The fence also prevents casual passers-by from trying to climb the tower out of curiosity. A "No Trespassing" sign should be posted on the fence.

However, in case of an observation site located on an agricultural land, the tower is generally not as high and a fence may affect the observation results. The fence can also obstruct agricultural work (where machinery is used), so it is often not set up at such sites. But in case of an observation site located far from town, measures against theft or deliberate destruction of measuring instruments are needed. For example, the deployment of a security guard or the installation of a security camera is effective at forest sites. The former is an especially practical measure to take at observation sites located in countries where labor costs tend to be low.

Communications

It is better to provide a telephone line to the site to ensure emergency contact, although this is not necessary when a cell phone can be used. It is even better if there is an Internet connection. Data can be retrieved online, but for data integrity, it is safer to record and store the data onsite.

1.3 Measurement variables: recommendations and order of precedence

Measurement variables required for flux measurement and analysis and for the use of flux data are listed below. Here, the variables are ranked as “essential”, “A,” “B,” or “C,” according to their order of precedence, mainly in terms of CO_2 flux measurement. Lower-ranked variables may be adopted or rejected based on the purpose of the study.

1.3.1 Variables essential for eddy covariance flux measurement (turbulence fluctuation method)

The following variables are essential for energy or CO_2 flux measurement.

1) Three-dimensional wind velocity fluctuation
2) Sonic virtual temperature fluctuation
3) Water vapor (density or volumetric mixing ratio) fluctuation
4) CO_2 (density or volumetric mixing ratio) fluctuation
5) Air temperature, humidity, and atmospheric pressure (These must be measured by sensors that have slow but stable responses)

1.3.2 Micrometeorological and hydrological variables

In addition to the eddy covariance technique, the mean value of the following micrometeorological and hydrological variables can be measured.

Micrometeorological and hydrological variables are used for flux analysis. In particular, variables that are ranked as “essential” in this section are necessary for checking the quality and interpolation of CO_2 flux and of the amount of net ecosystem CO_2 exchange.

Radiation

Although it is best to measure upward and downward shortwave, longwave, and photosynthetically active radiations (PARs) as well as radiations over and under the canopy, measurement of radiation over the canopy takes priority over the other measurements (Table 1.3-1). Net radiation can be calculated by subtracting the sum of the upward short and long-wave radiations from that of the downward short and long-wave radiations. Moreover, a spectroradiometer or radiation meter for a certain frequency domain can be set up for ground-based verification using remote sensing technology.

Basic micrometeorological variables

Air temperature, humidity, wind velocity, and wind direction at about the same height as the point of the eddy covariance measurement over the canopy are indispensable.

Measurements of the amount of precipitation and of the shallow ground temperature are also required.

Profile (vertical distribution) measurement variables

Table 1.3-2 shows the profile (vertical distribution) measurement variables.

To calculate CO_2 storage change, the CO_2 profile needs to be measured; the CO_2 storage change is required for the calculation of the net ecosystem CO_2 exchange (NEE) of the plant community. The radiation (solar radiation and PAR) profile can be measured for a detailed investigation of the photoenvironment of the complicated forest crown layer.

Table 1.3-1 Variables required for flux measurement (radiation).

	Over the canopy		**Under the canopy**	
	Downward	**Upward**	**Downward**	**Upward**
Shortwave radiation	essential	essential	A	A
Longwave radiation	A	A	B	B
Photosynthetically active radiation	essential	essential	A	A
Spectroradiation (radiation of different wavelengths)	B	B	C	C
Net radiation	B	B	C	C

Table 1.3-2 Profile (vertical distribution) measurement variables.

Measurement variables	**Rank**
Air temperature profile	B
Humidity profile	B
Wind velocity profile	B
Soil temperature profile	A
PAR profile	B
CO_2 density profile	A

Other

Measurement variables can be adopted or rejected according to the characteristics of the observation site and the purpose of the study (Table 1.3-3).

Table 1.3-3 Other measurement variables.

Measurement variables	Rank
Atmospheric pressure	A
Soil heat flux	A
Temperature of canopy surface, leaf surface temperature	C
Snow depth	A
Snow water equivalent	C
Water quality of precipitation	C
Soil moisture profile	A
Groundwater level and quality	C
Amount of fog drip (precipitation resulting from thick fog condensing on leaves)	C
Water level, water temperature, and amount of irrigation water	B
Stem temperature: Required to calculate the amount of heat stored in stems and to estimate stem respiratory volume	C
Amount of water, snow, or other moisture adhering to the canopy	C
Sap flow velocity or sap flow rate	C
Amount of rainfall interception (throughfall, stemflow) and associated water quality	C
Amount of runoff and associated water quality	C

1.3.3 Structure and basic characteristics of a plant canopy

It often requires a great deal of effort to investigate the structure and basic characteristics of an ecosystem, especially in a forest of tall trees. For measurement variables that display only small secular changes, data obtained from a single observation conducted during the measurement period is enough to help clarify the condition of the site.

To determine the carbon balance of the agricultural ecosystem, it is necessary to measure the biomass and carbon content in different parts of each crop in order to estimate the amount of agricultural product removed from the study site at harvest. The influx of carbon accompanying the application of organic materials such as compost and the outflow of carbon accompanying the burning of crop residues are essential measurement variables when those management methods are used (Table 1.3-4).

Table 1.3-4 Measurement variables of an ecosystem.

Measurement variable	**Rank**
LAI (Seasonal variation of vertical integrated value）	A
LAI (Vertical distribution profile)	B
Phenology observation	B
Canopy surface image	B
Hemispherical image from forest floor	C
Amount of litterfall	C
Soil survey	B
Inventory to estimate above-ground biomass	A
Survey of tree roots	C
Amount of agricultural products removed at harvest	A
Amount of organic materials applied (e.g., compost)	A
Amount of crop residues burnt in the field	A
Leaf photosynthetic characteristics	B
Nitrogen content of tree leaves	B

Related information for chapter 1

Further reading

AmeriFlux Standards: Guidelines/SOPs http://public.ornl.gov/ameriflux/sop.shtml

Fluxnet-Canada Measurement Protocols Working Draft Version 1.3:

http://www.fluxnet-canada.ca/pages/protocols_en/measurement%20protocols_v.1.3_background.pdf

Devices and instruments

1.2

Monorail

- Koei Sangyo Co., Ltd, Japan http://www.koei-m.co.jp/ [in Japanese]

Tower

- Nippon Light Metal Company, Ltd., Japan (Nikkei Forest Tower) http://www.nlmetal.com/ http://www.nikkeikin.co.jp/pages/products/products_p4/4b/4b_040.html [in Japanese]
- CQ Tagami Corporation, Japan (Wireless antenna tower) http://www.cq-tagami.jp/ [in Japanese]
- Eagle Clamp Co., Ltd., Japan (Fall-prevention devices) http://www.eagleclamp.co.jp/english/

Electrical construction

- Kandenko Co., Ltd., Japan http://www.kandenko.co.jp/en/

Underground cable protective tube

- Furukawa Electric Co., Ltd., Japan (EFLEX) http://www.furukawa.co.jp/english/

Power generation system and Power supply devices

- Natural sky network, Japan http://www.natural-sky.net/ [in Japanese]
  Selection of solar power generation system and example of electric power calculation: http://www.natural-sky.net/learn/index_study-solar.html [in Japanese]
- Campbell Scientific, Inc., US http://www.campbellsci.com/

Lightning surge countermeasures

- Sankosha Co., Ltd., Japan (Y08U-75B) http://www.sankosha.co.jp/en/
- Fuji Electric Technica Co., Ltd., Japan http://www.fujielectric.co.jp/technica/ [in Japanese]
- Shoden Co.,Ltd., Japan http://www.sdn.co.jp/eng/
- Morinaga Electronic Co., Ltd., Japan http://alp-plp.co.jp/eng/

Storerooms

- Yodogawa Steel Works, Ltd., Japan http://www.yodomonooki.jp/ [in Japanese]
- INABA SEISAKUSHO Co., Ltd., Japan http://www.inaba-ss.co.jp/ [in Japanese]

2

Observation of Turbulence

2.1 Ultrasonic anemometer thermometers (SATs)

When scalar fluxes are measured using the eddy covariance method, the fluctuating components of the wind velocity need to be measured regardless of the type of scalar of interest. In the observation of the fluxes across the interface between the Earth's surface and the atmosphere, the vertical exchanges of energy and scalar quantities are important. Therefore, flux observation requires measurements of the fluctuating component of the vertical wind velocity (w [ms^{-1}]), w' [ms^{-1}]. In order to accurately estimate the exchange of energy and scalar quantities by turbulence, the observation system needs to be capable of measuring w' at a sampling rate of approximately 10 Hz or higher. The observation instrument also needs to be able to make measurements without drifting on the time scale of at least several days and needs to be durable enough to make field observations for a year to several years. Ultrasonic anemometer thermometers (SATs hereafter) are currently the only sensors available that meet the above-mentioned requirements.

Principle of measurement

The principle of measuring the wind velocity components and the sonic virtual temperature using a SAT is explained below. A SAT measures the wind velocity and the speed of sound in the air, c, along the straight line (path) between a pair of sensors (transducers) that face each other. The path length of a SAT typically used in field observations (span length) is approximately 0.05 ~ 0.20 m. The pair of sensors are internally equipped with transceivers made of acoustic elements. Acoustic signals are transmitted from one transceiver to the other in both directions. From the time required for an acoustic signal to travel between the transceivers in two directions, t_1 [s], and t_2 [s], the wind velocity component parallel to the path, v_d [ms^{-1}] and the speed of sound, c_s [ms^{-1}] can be calculated from the following relationships. For the span length of d [m], the travel times, t_1 and t_2 are expressed as

$$t_1 = \frac{d}{c_s + v_d}, \quad t_2 = \frac{d}{c_s - v_d} \qquad \text{(2.1-1a, 2.1-1b)}$$

respectively. By subtracting the inverse of Equation 2.1-1b from that of Equation 2.1-1a, the following relationship can be obtained to calculate v_d:

$$v_d = \frac{d}{2}\left(\frac{1}{t_1} - \frac{1}{t_2}\right) \qquad \text{(2.1-2)}$$

By taking the sum of the inverse of Equation 2.1-1a and that of Equation 2.1-1b and using the relationship between the speed of sound, c_s, and the sonic virtual temperature, T_v [K]: $c_s{}^2 = 403T_v$, the following equation can be obtained for calculating T_v:

$$T_v = \frac{c_s^2}{403} = \frac{1}{403}\left[\frac{d}{2}\left(\frac{1}{t_1}+\frac{1}{t_2}\right)\right]^2 \qquad (2.1\text{-}3)$$

The air temperature can be calculated from the sonic virtual temperature measured by a SAT. The calculation procedure requires corrections for the effects of the horizontal wind (cross-wind contamination) and the water vapor content as described in a later section (pp. 38 ~ 39). Refer to Kaimal and Gaynor (1991) and Hignett (1992) for the details of the corrections.

Types of SATs

The SATs that are generally used for field observations are three-dimensional SATs (3D-SATs). They are equipped with three pairs of sensors, and the three orthogonal components of the wind velocity parallel to the x, y, and z axes (or the *u*, *v*, and *w* axes) are output. (The z axis or *w* axis indicates the axis aligned in the direction of gravity.) Unlike one-dimensional SATs which measure the scalar flux in only the vertical direction, the use of 3D-SATs allows calculations of momentum fluxes, coordinate transformations in the post-data acquisition stage, and correction for the cross-wind effect on the sonic virtual temperature acquired by the SATs.

There are various types of 3D-SATs. Commercially available 3D-SATs are durable enough for field observations and are characterized by a fair level of reliability.

Specifications of well-trusted SATs that have often been deployed for observations both in Japan and abroad are summarized in Table 2.1-1. The 3D-SATs that are frequently used in observations are classified below according to the configuration of the frame that supports the sensors (probe).

Vertical path 3D-SATs

Some 3D-SATs measure the vertical component of the wind velocity with a pair of sensors that constitute a path parallel to the vertical axis and measure the horizontal components of the wind velocity with two pairs of sensors that lie in a horizontal plane. These 3D-SATs will be referred to as vertical path 3D-SATs in this section. When the paths are orthogonal to one another, the 3D-SATs are called orthogonal type (orthogonal probe). Vertical path 3D-SATs include the TR-61A (Table 2.1-1), the TR-61C (Table 2.1-1, Photo 2.1-1(a)), and the TR-90AH all manufactured by SONIC CORPORATION, Japan (former Kaijo Sonic Corp.) and the "K" Style Probe (Table 2.1-1, Photo 2.1-1(b)) manufactured by Applied Technologies Inc., US (ATI). (A measuring and control unit together with a TR-** probe is identified by the model number DA-600.) Of the probes listed above, the TR-61C and the "K" Style Probe are orthogonal probes.

Slanted path 3D-SAT

Some 3D-SATs are equipped with three pairs of sensors which are arranged in such a way that the upper sensors of all three pairs are on the vertices of an equilateral triangle as are the lower sensors of all three pairs. Furthermore, the sensors are attached so that the measurement paths are slanted from the vertical axis and the center of the three measurement paths intersect. (See Photo 2.1-1.) These 3D-SATs are called slanted path 3D-SATs here, and can be classified roughly into two types. The first type is called an omni-directional probe. The supporting post of the omni-directional probe is located underneath the sensors, and the probe is rotationally symmetrical around an axis in the vertical direction. In contrast, the sensors in the second type (referred to as boom probes here) are supported by arms from the top and the bottom; the supporting arms meet at a height that is mid-way between the upper and lower sensors. Examples of omni-directional probes are the TR-61B (Table 2.1-1; an option with the DA-600) and the SAT-540/550 (Table 2.1-1, Photo 2.1-1(c)) manufactured by SONIC, the WindMaster and the R3 manufactured by Gill Instruments Ltd, UK. (Table 2.1-1), the Model 81000 manufactured by R. M. Young Company, US, and the USA-1 (previous model) manufactured by Metek Meteorologische Messtechnik GmbH, Germany. Boom probes include the CSAT3 manufactured by Campbell Scientific Inc, US. (Table 2.1-1, Photo 2.1-1(d)) and the HS manufactured by Gill (Table 2.1-1).

Tips!

Slanted path probes were developed subsequent to vertical path probes. Slanted path probes were designed to minimize the disturbance of the horizontal wind, the magnitude of which is usually larger than that of the vertical wind. However, because the three components of the wind velocity are calculated from the outputs from all three sets of sensors, the failure of any one set of sensors may lead to a loss of data for the sonic virtual temperature and all of the x-, y-, and z- wind velocity components (Hirano and Saigusa, 2007).

Tips 2.1-1

Table 2.1-1 Specifications of widely-used SATs.

Manufacturer	Model/ probe	Path-length [m]★	Configuration (angle between horizontal plane and vertical-wind sensor path)	Probe weight [kg]	Output	Power consumption	Flow distortion references
SONIC	DA-600 (TR-61A)	0.2	Vertical path (90°; 120° between the horizontal-wind sensor paths)	4.3	Digital / Analog	<30W	Kondo and Sato (1982), Hanafusa *et al*. (1982), Wieser *et al*. (2001), Ito *et al*. (2001)
	DA-600 (TR-61B)	0.2	Slanted path, omni-directional probe (45°)	7.9	Digital / Analog	<30W	Wieser *et al*., (2001)
	DA-600 (TR-61C)	0.2	Vertical path, orthogonal probe (90°)	5	Digital / Analog	<30W	Wyngaard *et al*. (1985) ※1, ※2, Shimizu *et al*. (1999) ※1, ※2, Wieser *et al*. (2001)
	SAT-540/550	0.1	Slanted path, omni-directional probe (45°)	2.7	Digital / Analog	4W	None
ATI	"K" Style Prob	0.15	Vertical path, orthogonal probe (90°)	<1.0	Digital	1.2W	Kaimal *et al*. (1990) (see also ATI homepage) ※1, ※2
Campbell	CSAT3	0.115	Slanted path, boom probe (60°)	1.7	Digital / Analog	1.2 W (operating at 20 Hz)	Cristen *et al*. (2001)
Gill	WindMaster/ WindMaster pro	0.144	Slanted path, omni-directional probe (45°)	0.9 / 1.7(-pro)	Digital / Analog (optional)	0.66W	van der Molen *et al*. (2004)※2, Nakai *et al*. (2006)※2
	R3(-50, 100)	0.144	Slanted path, omni-directional probe (45°)	0.9	Digital / Analog	3.6W	van der Molen *et al*. (2004)※2, Nakai *et al*. (2006)※2
	HS(-50, 100)	0.144	Slanted path, boom probe (48.75°)	2.5	Digital / Analog	3.6W	Cristen *et al*. (2001)

★ Even within the same model, the path length may differ by a few mm.
※1 Evaluation of transducer shadowing only, ※2 correction formula available

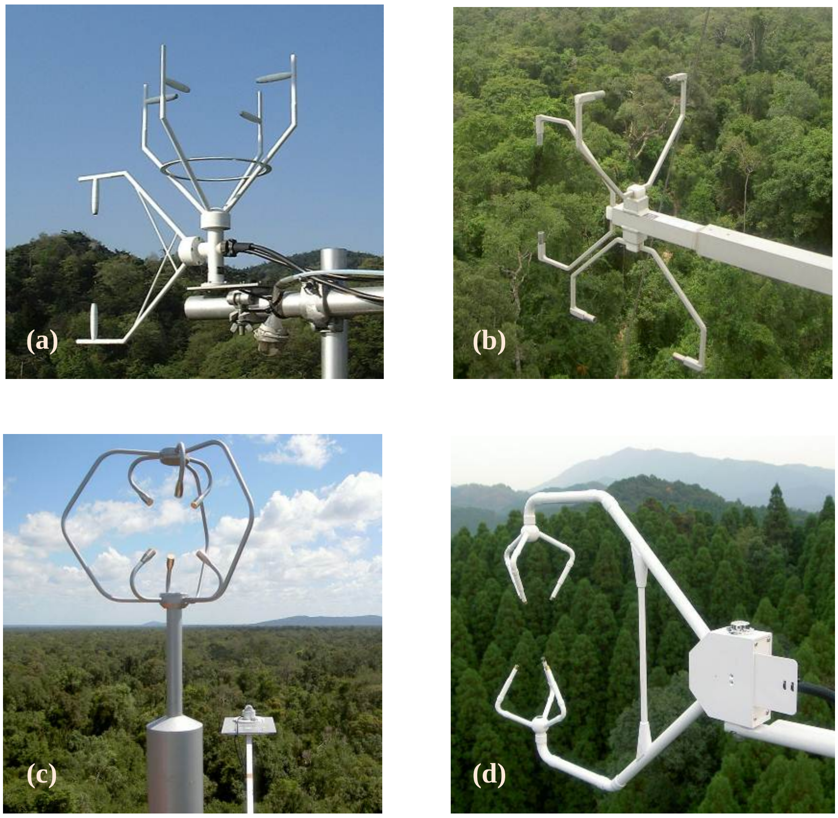

Photo 2.1-1 Configuration of SAT probes: (a) SONIC TR-61C (vertical path, orthogonal probe, Yamashiro forest hydrology research site), (b) ATI "K" Style Probe (vertical path, orthogonal probe, evergreen forest in Kompong Thom Province, Cambodia), (c) SONIC SAT-540 (slanted path, omni-directional probe, evergreen forest in Kompong Thom Province, Cambodia), (d) Campbell CSAT3 (slanted path, boom probe, Kahoku Experimental Watershed).

Tips!

All the 3D-SAT models in Table 2.1-1 output the upward vertical component of the wind velocity as positive values. However, the sign convention of the horizontal wind velocity components varies among the models. Fig. 2.1-1 shows the sign convention of the horizontal coordinate system of some of the SATs in Table 2.1-1.

Tips 2.1-2

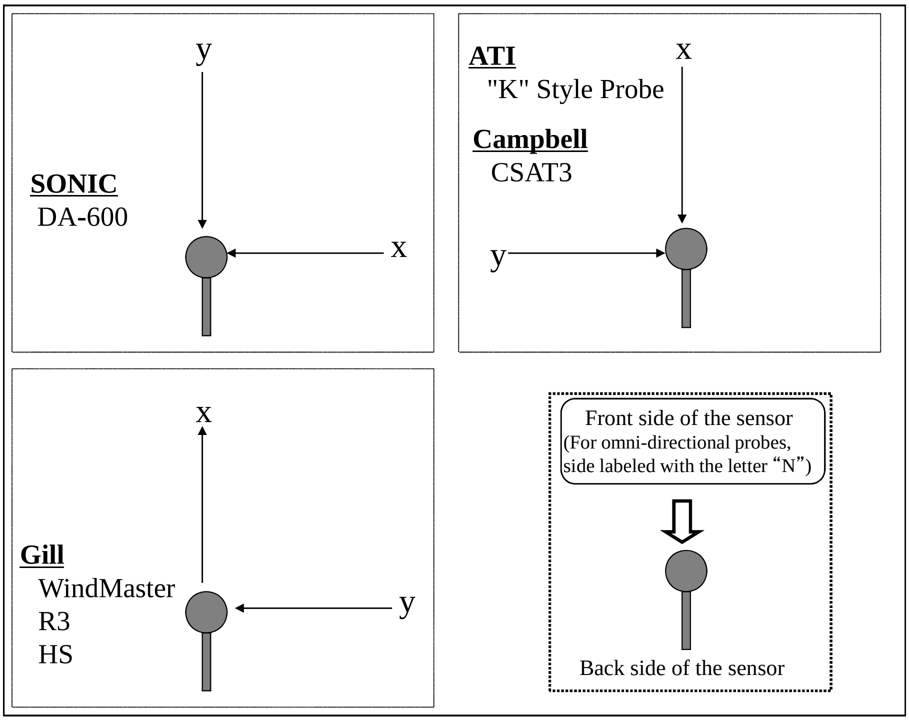

Fig. 2.1-1 Sign conventions of widely-used SATs.

Deployment

Selection of deployment location

When a SAT probe is installed on a tower, in order to avoid the influence of the tower and the SAT itself on the wind velocity measurements, the following precautions need to be taken into account:

1) Deploy the SAT probe on the top of the tower or on a long boom to keep the SAT probe away from the tower.
2) Deploy the SAT probe pointing into the direction of the prevailing wind and the direction in which the flow distortion by the tower and the probe itself is minimized. (Flow distortion will be discussed on p. 37.)

Regarding 1), it is desirable to use a boom that is more than 1.5 times the width of the tower through which wind passes (Hirano and Saigusa, 2007). When the use of such a boom is not feasible, deploy the SAT as far as possible from the tower taking into account the tasks required for deployment and maintenance. Caution 2) is especially important for the deployment of a SAT with a structure which disturbs the wind flowing through the backside of the probe, e.g., the TR-61A and TR-61C manufactured by SONIC, the HS manufactured by Gill, and the CSAT3 manufactured by Campbell. (The backside of a probe usually corresponds to the side to which cables are connected.)

Probes and parts

In the process of deploying a SAT probe, fittings are required to attach the probe to the tower. In most cases, the SAT probe (or the boom provided by the SAT manufacturer) is secured to a base by screws or U-bolts. The base, in turn, is secured to the tower by half-clamps and/or U-bolts. The simplest base can be made by drilling holes in a flat plate. Because the size of the base and the positions of the holes depend on the SAT and the tower specification, the investigator usually needs to build a base on his/her own. While plywood is easy to fabricate, it can warp and deform. Thus, when the base is used for long-term observation, metal such as stainless metal or aluminum is recommended for the base. Alternatively, sufficiently dried solid timber can be used if appropriate corrosion protection is applied.

Some models of SATs come with signal converters that are separate from the probes. For these models, additional installation space and fittings are required for the signal converters.

Tips!

The DA-600 (TR-61A, B, and C) manufactured by SONIC consists of a probe, a signal conversion box (waterproofed), and an output unit (non-waterproofed). The CSAT3 manufactured by Campbell consists of a probe and a signal conversion box (waterproofed). Waterproofed SAT components are usually deployed outdoors while non-waterproofed SAT components are usually placed inside a sheltered space such as a hut in which the components are protected from rainfall.

Tips 2.1-3

Cables

The signal cables of SATs are usually made of 5 to 20 cores, thus the weight of a signal cable can become large depending on the length of the cable and the SAT model. (For example, the signal and power cables of the DA-600 manufactured by SONIC weigh about 150 gm^{-1}.) It is desirable to determine the appropriate cable length in advance so that it will not be heavier than necessary for hauling and handling. Secure the bends in the cables to the tower with weather-resistant cable ties (e.g., Insulok, HellermannTyton, UK) and vinyl tape while making sure that the bends in the cables do not get damaged by vibrations caused by strong wind. Furthermore, secure the cables running along the tower at appropriate intervals so that large tension loads are not placed on the cables themselves.

Leveling adjustment and tilt check

In principle, the SAT probe should be deployed in such a way that the z-axis component of the wind velocity is parallel to the direction of gravity. (The x-y plane of the SAT probe is horizontal.) The time and effort to adjust the leveling of the SAT can be reduced significantly if a simple level is added to the above-mentioned base used for installing the SAT. (See above section on “Probes and parts”.) Nonetheless, the horizontal deployment of a SAT may not be strictly feasible in some cases. When flux measurements are made over sloped topography and the blow-up and blow-down angle of the wind velocity for the site is known from preliminary measurements, the SAT may be tilted by that angle for deployment. In either case, the tilt of the SAT should be measured with an inclinometer after the SAT has been stabilized; so that the measured vales of the tilt can be used to correct the wind velocity and direction as necessary. Sometimes, the tower tilt or tower vibrations may be of concern because of the weight of workers on the tower or strong wind, respectively. In this case, the use of a self-recording inclinometer is recommended to record the tower tilt and/or vibrations.

Tips!

A bubble level is equipped on the probe of both the CSAT3 manufactured by Campbell and the DA600 (TR-61A) manufactured by SONIC. An inclinometer is built into the probes of the R3-100, R3A-100 and HS manufactured by Gill. (An inclinometer can be added as an option for the R3-100 or R3A-100.)

Tips 2.1-4

Data acquisition

The output values of a deployed SAT can be recorded by connecting its signal cable to a data logger and setting the data logger appropriately. (For setting the data logger, refer to Section 2.6 “Data logger”.)

Depending on the model of the SAT, its output can be acquired either as an analog voltage signal or as a digital signal. (Digital signal outputs can be acquired using the Campbell SDM port or the RS-232C port. Many SAT models are able to output both analog and digital signals.) An advantage of analog signals is that they can be easily acquired and recorded by a large number of data loggers. On the other hand, an advantage of digital signals is that the output values are subject to less noise than those acquired as analog signals.

In Appendix 2.1-1, a sample program is given for acquiring digital data with a CR1000 from an ATI "K" Style Probe. In this example, pin numbers 3 and 2 of the RS-232C connectors are connected directly to the C1 and C2 ports of the CR1000, respectively. The sample program may serve as a useful reference for recording digital data outputs from the SATs manufactured by SONIC or Gill. (However, there is no guarantee that the program will work in all situations.)

When data from a CSAT3 are output digitally to a data logger such as a CR1000, an SDM cable can be used for a simple and easy connection between the sensor and the data logger. The SDM connection requires less electricity than other connections, and a sample program for the operation of the system is available in the CSAT3 manual. Although the length of the SDM cable supplied by the manufacturer is normally 7.62 m, the user may need to extend its length in some circumstances. In this case, the numerical value in the parenthesis that follows the control command "SDMspeed" for Campbell data loggers needs to be set to a larger value. (The numerical value used for SDMspeed is approximately 30 for an SDM cable with a length of 7.62 m.)

Tips!

SDM (Synchronous Devices for Measurement) is a protocol established by Campbell for improving the communication control between a data logger and peripheral devices. Connection of a data logger to peripheral devices via SDM enables synchronized data acquisition at a high speed. Therefore, the use of SDM is suitable for measurements such as those for the eddy covariance method in which multiple signals are acquired simultaneously at a high frequency and in which care is necessary to correct for the mis-synchronization of the signals. The maximum communication speed of SDM (SDM clock rate) changes according to the number of sensors that are connected, the scan interval, and the cable length. Thus, according to the measurement system to be used, the SDM clock rate needs to be set to an appropriate value in order to avoid communication errors.

Tips 2.1-5

Maintenance

Generally, a SAT requires very little maintenance after its deployment. Even when the coating material on the SAT becomes discolored or peels off due to its deployment outdoors, the influence of these coating modifications on the measurement result is extremely small if it exits at all. The data output can be influenced by nearby lightning strikes or instantaneous power outages as well as rain drops within the measurement paths or on the sensors. In these cases, the data output is characterized by abnormal values. However, as long as no similar abnormality can be detected in the data from a few days without rain after the occurrence of the abnormality, the SAT measurement can be continued without any adjustment. On the other hand, if abnormal values occur intermittently and their cause is unknown, turn in the SAT to the manufacturer for repair and replace it by a backup SAT immediately.

Unless data abnormalities such as those discussed above are observed, the following procedures are sufficient for routine SAT maintenance:

- If objects such as spider webs are in the SAT measurement paths, remove the objects.
- If the surfaces of the sensors are extremely dirty, wipe them with a soft cloth wetted with alcohol or distilled water.

In addition, in the case of a long-term SAT deployment, it is desirable to follow the procedures below every few months to a year.

- Check the wind velocity offset.
- Correct the sonic virtual temperature by referring to the data collected by a thermo-hygrometer near the SAT height.
- Check if the tilt angle has changed from the time of deployment and adjust it if necessary.

Although it is recommended that the wind velocity offset be checked indoors, the offset can also be checked on a SAT while it is still deployed. In this case, cover the SAT with a large plastic bag and check if the values of the three wind velocity components fluctuate near zero. If the offset values are large, the SAT is likely defective; the data acquired after the offset check need to be examined quickly and carefully to make a decision about repairing the SAT.

Tips!

The probe head of the TR-61 (A, B, C) manufactured by SONIC can be easily changed by the user. When an abnormality arises on the TR-61, it can sometimes be resolved by replacing the probe head which includes the sensors. Because a backup probe head is not as expensive as a SAT itself, it is desirable to have a backup probe head ready when a TR-61 probe is used.

Tips 2.1-6

Tips!

Abnormal output data from SATs are frequently associated with the presence of raindrops. When the probe of a slanted path SAT is deployed with its x-y plane perpendicular to gravity, the sensors are tilted, and raindrops can slide off easily, which is considered an advantage of slanted path SATs. Furthermore, as an option to guide raindrops away from the measurement paths, mesh fabric called wicks can be placed on the sensors of the CSAT manufactured by Campbell. Due to their presence around the sensors, wicks may become a source of additional disturbance for the wind in the vicinity of the sensors. However, from the size of the wicks, it is speculated that their influence on the wind is small. Although caution is necessary, wicks can be added and removed by the user. Therefore, it is possible to use wicks only during the rainy season in which the influence of rainfall on the sensors is expected to be large. In principle, the method of raindrop removal with wicks is also applicable to SATs of any other manufacturers.

Tips 2.1-7

Measurement errors intrinsic to SATs

Errors associated with averaging over the measurement path

The wind velocity and signal speed (speed of sound) obtained by a SAT are those averaged over the measurement path. Fine-scale fluctuations of a variable that occur at scales smaller than the path length are averaged, i.e., path-length averaging effect or line-averaging effect. Fluctuations of a variable that occur at finer scales than the path length are sometimes sought, for example, in the case of measurements conducted near the ground surface. In such cases, a SAT which is equipped with short paths and a non-orthogonal probe (i.e., a configuration in which multiple paths intersect at the same point in space) should be utilized.

The amount of missing high-frequency signals to be corrected due to path-length averaging varies according to the atmospheric stability (e.g., Kristensen and Fitzjarrald, 1984). On the other hand, some studies, such as Aubinet *et al*. (2000), report that sufficient corrections of the signals for path-length averaging can be made with the comprehensive method proposed by Moore (1986) which does not depend on the atmospheric stability.

When a slanted path 3D-SAT is used, the wind velocity and sonic virtual temperature are calculated from the measurements made over the three paths of the SAT. For this reason, caution is necessary for correcting missing high-frequency signals due to path-length averaging (Horst and Oncley, 2006).

Errors associated with SAT-induced flow distortion

When a SAT is used for observations, its probe is fixed in the wind velocity field. It is thus believed that flow distortion is induced by the sensor and the frame of the SAT itself. Blockage of the wind by the sensors is called “transducer shadow”. This effect becomes the main source of flow distortion when using a vertical path probe in which two pairs of sensors are placed on a horizontal plane. On the other hand, when a slanted path probe is used, it is likely that the supporting post and frame which support the sensors induce flow distortion mostly in the vertical wind velocity.

Generally, flow distortion is evaluated using wind tunnel experiments. The results of wind tunnel experiments for some of the SAT probes can be found in the references given in Table 2.1-1. However, it remains controversial whether the results of wind tunnel experiments on flow distortion can be applied to observational data collected in field experiments. While a number of applications of the results of wind tunnel experiments to field observations have been reported (e.g., Kondo and Sato, 1982; Kaimal *et al*., 1990; Nakai *et al*., 2006; Saitoh *et al*, 2007), studies opposing such applications have also been published (e.g., Hanafusa *et al*., 1982; Ito *et al*, 2001; Ishida *et al*., 2004).

Model recommended for its small measurement errors

All the commonly used SATs have achieved an acceptable level of reliability. Particularly, the models listed in Table 2.1-1 have earned good reputations in terms of reliability. Of these models, the CSAT3 manufactured by Campbell, due to its small intrinsic errors and high measurement accuracy, is currently considered the most trusted SAT model (e.g., Mauder *et al*., 2007).

No formula is yet available for flow distortion correction for the CSAT3 that is based on a wind tunnel experiment. Therefore, when flow distortion corrections are necessary for the measurements made by a CSAT3, the investigator may need to conduct his or her own wind tunnel experiment. Furthermore, when wind flows from the backside of the CSAT3 probe, the wind velocity field is disturbed by the boom that supports the probe (Christen *et al*., 2001). Thus, the influence of the boom on CSAT3 measurements needs to be taken into consideration.

Correction of SAT-measured temperature

Correction of horizontal wind contamination

The variable c_s in Equations 2.1-1 and 2.1-3 is strictly the speed of sound waves that are measured in the path of a SAT. The actual distance traveled by the sound waves along the path becomes longer than the path-length due to the wind component normal to the path (cross wind), v_n [ms^{-1}] (Kaimal and Finnigan, 1994). Accordingly, the values of c_s in Equations 2.1-1 and 2.1-3 are smaller than the actual (true) speed of sound, c_t [ms^{-1}]. The actual sonic virtual temperature, T_{vt} [K], is the temperature that is evaluated from the value of c_t. Therefore, in order to calculate T_{vt}, corrections are required for the cross-wind effect. The following relationship holds between c_s and c_t with the presence of a cross wind, v_n:

$$c_s^2 = c_t^2 - v_n^2 \quad (2.1\text{-}4)$$

Therefore,, the following can be obtained.

$$T_{vt} = \frac{c_t^2}{403} = \frac{1}{403}\left[\frac{d^2}{4}\left(\frac{1}{t_1}+\frac{1}{t_2}\right)^2 + v_n^2\right] \quad (2.1\text{-}5)$$

When the sonic virtual temperature is evaluated from the vertical path of a vertical path 3D-SAT, v_n is equivalent to the horizontal wind velocity measured by the SAT. In this case, the cross-wind effect can be corrected relatively easily. However, a somewhat complex method is necessary for the correction of the cross-wind effect when slanted path 3D-SATs are used, particularly for the models in which the sonic virtual temperature is evaluated from the measurements averaged over the three paths (Liu *et al*., 2001).

Tips!

Among the slanted path 3D-SATs in which the sonic virtual temperature is evaluated from the measurements averaged over the three paths of an instrument, the CSAT3 manufactured by Campbell outputs a sonic virtual temperature which has been corrected for the cross-wind effect. Furthermore, concise procedures for correcting the cross-wind effect for the WindMaster, R3, and HS manufactured by Gill can be found in their product manuals.

Attention: User Manual Issue 04 (April, 2009) for the WindMaster & WindMaster Pro states that the virtual temperature output by the SAT has been corrected for the cross-wind effect. Whether the output value of the virtual temperature has been corrected for the cross wind may depend on whether the data are collected by an old or a new model. Thus, the investigator needs to inspect the manual for the details on cross-wind correction.

Tips 2.1-8

Water vapor correction

Rigorous calculation of the sensible heat flux requires the use of the air temperature, T_a [K], rather than the sonic virtual temperature, T_{vt}, that is calculated in Equation 2.1-5. The sonic virtual temperature, T_{vt}, can be related to the air temperature, T_a, as:

$$T_{vt} = \left(1 + 0.32\frac{e}{p}\right)T_a \qquad (2.1\text{-}6)$$

where p [Pa] and e [Pa] are the atmospheric and water vapor pressures, respectively. If $e << p$, $\left(1 + 0.32\frac{e}{p}\right)^{-1} \approx 1 - 0.32\frac{e}{p}$; and also $0.32\frac{e}{p} \approx 0.32\frac{e}{p-e} \approx 0.32q\frac{m_d}{m_W} \approx 0.51q$. Here, m_d is the molecular weight of dry air [kgmol^{-1}], m_W is the molecular weight of water vapor [kgmol^{-1}], and q is the specific humidity [kgkg^{-1}]. Accordingly, the relationship

$$T_a = (1 - 0.51q)T_{vt} \qquad (2.1\text{-}7)$$

is a close approximation for Equation 2.1-6. Similarly, the fluctuating components of T_a, $T_{vt,}$ and q can be related to one another as

$$T_a' \approx T_{vt}' - 0.51\overline{T_{vt}}q' \qquad (2.1\text{-}8)$$

The effect of water vapor on the sensible heat flux evaluated from SAT measurements can be corrected in the following way: if the instantaneous values of air pressure and water vapor pressure are available, the instantaneous value of T_a can be calculated from that of T_{vt} and Equation 2.1-6. The calculated instantaneous value of T_a can in turn be used to calculate the sensible heat flux. Alternatively, the effect of water vapor can be corrected in an approximate sense using Equation 2.1-8 together with the individually calculated values of sonic virtual temperature flux, $\overline{w'T_{vt}'}$, and moisture flux, $\overline{w'q'}$.

Appendix 2.1-1: Sample program

The following is a sample program for acquiring ATI "K" Style Probe data using a Campbell CR1000 data logger and the compact flash module, CFM100 (Campbell):

```
‘CR1000 Program for ATI SAT

'Declare Variables and Units
PUBLIC ATI_K as STRING * 100
PUBLIC SAT(4)

Units SAT=*ms-1/Deg C

'Define Data Tables
DataTable(Table1,1,-1)
       DataInterval(0,100,mSec,10)
       CardOut(1, -1)
       Sample(4, SAT, FP2)
'      Sample(1, ATI_K, string)
        'If activate, raw strings will be recorded
EndTable

'Main Program
BeginProg
       SerialOpen (Com1, 9600, 0, 0, 500)
        'The 3rd number corresponds to "Parity, Bits length, Flow ctrl"
        Scan(100,mSec,10,0)
        SerialIn(ATI_K, Com1,100,13,500)
          'ASCII"13" is Carriage Return
        SplitStr(SAT,ATI_K," ",4,0)

          'The last “0” corresponds to split by number
        CallTable(Table1)
       NextScan
EndProg
```

2.2 Open-path CO_2/H_2O gas analyzers

2.2.1 Measurement of fluctuating CO_2 concentration by an open-path gas analyzer

An open-path CO_2 gas analyzer measures the number of CO_2 molecules within the open path of the instrument. Because the CO_2 measurement by the instrument is based on the absorption of infrared energy by CO_2, the attenuation of infrared radiation is the basic output value from the analyzer. The output value is converted to the number of CO_2 molecules per unit volume (CO_2 number density [mol-CO_2m^{-3}]) with the use of the calibration coefficients determined by the manufacturer or the user. Therefore, the user needs to be aware that the physical variable being measured is CO_2 number density rather than the mixing ratio ([ppm] or [mol-CO_2mol-dry-air^{-1}]) which is used to label the calibration gas and also to calculate the fluxes.

The general characteristics of an open-path CO_2 gas analyzer (open-path gas analyzer hereafter) relative to a closed-path gas analyzer (Section 2.3) are as follows: 1) the response time of an open-path gas analyzer to the fluctuating CO_2 is faster; 2) an open-path gas analyzer requires less power; 3) the overall configuration, i.e., the analyzer and its peripheral components, of an open-path gas analyzer is simpler; 4) the volume of the sensor head is larger for an open-path gas analyzer. (The sensor head becomes an obstruction to measurements at the measurement height.); 5) automated calibrations of an open-path gas analyzer are difficult; 6) accurate measurements of air temperature and pressure within the open path are not easily obtained, and also the magnitude of the correction term of the so-called WPL correction (Webb *et al*., 1980) is larger. Characteristics 1 to 3 are generally considered advantages of an open-path gas analyzer, while characteristics 4 to 6 are generally considered disadvantages.

Types of available open-path gas analyzers

Table 2.2-1 summarizes the major open-path gas analyzers that are available as commercialized products. The measurement principle of all the products is the same, that is, their measurements are based on the infrared absorption characteristics of CO_2 molecules. All the sensors listed in Table 2.2-1 are also equipped with interference filters for the infrared absorption waveband of H_2O molecules. Thus, all the sensors are able to measure the number of H_2O molecules per unit volume (mol-H_2Om^{-3}) simultaneously with that of CO_2. The details of the measurement principle and the structure of typical open-path gas analyzers are summarized in Kohsiek (2000). Kohsiek (2000) also gives the details of the cross sensitivity (see next paragraph) and a method for evaluating the cross sensitivity.

When CO_2 is measured by an open-path gas analyzer, the presence of H_2O changes the infrared absorption characteristics of CO_2 molecules. The effect of H_2O molecules on the measurement of the CO_2

number density (cross sensitivity) needs to be taken into consideration to evaluate the CO_2 number density accurately (Kohsiek, 2000). The control box of the LI-7500 (LI-COR, Inc., US) takes into account the cross-sensitivity (LI-COR, 2004), however, the E-009 (Advanet, Inc., Japan) and the OP-2 (ADC BioScientific Ltd., UK) do not adjust their measurement outputs for the cross-sensitivity. Furthermore, the indoor experiments of Leuning and King (1992) and Leuning and Judd (1996) on the cross-sensitivity of the E-009 showed that the characteristics of the cross-sensitivity of individual instruments vary according to the serial numbers even within the same model. Therefore, when the E-009 or the OP-2 is used for observations, the degree of cross-sensitivity needs to be assessed with indoor experiments such as those of Kohsiek (2000) or from the shape of the co-spectrum (Monji, 2003).

Table 2.2-1 Open-path CO_2 gas analyzers.

Model	**Manufacturer**	**Path length**	**Outside dimensions*** **(diameter and length)**	**Weight***	**Output signal**
LI-7500	LI-COR	12.5 cm	6.5×30 cm	0.75 kg	0-5 V, RS-232C, SDM**
E-009***	Advanet	20 cm	11×45.5 cm	-	–5 ~ 5 V
OP-2	ADC	Multiple folded path (20 cm×4)	7.6×37 cm	1.1 kg	–5 ~ 5 V

* Outside dimension and weight are those of the sensor head

** Synchronous Device for Measurement communication protocol of Campbell

*** This product has been discontinued.

A commercially available open-path gas analyzer usually consists of a sensor head, a control box, a power supply unit and a mountable calibration tube. Furthermore, accessories such as instrument-specific software are available for some of the commercially available open-path gas analyzers. When selecting an open-path gas analyzer, the user needs to take into consideration the cable lengths because the length of the cable between the sensor head and the control box as well as the length of the cable for the output signals of the measured values are limited in some models of open-path gas analyzers. Regarding the LI-7500, the value of the time lag of the output signal and the deployment method of the analyzer vary among its product model which can be identified by the serial number. When the LI-7500 is selected for use, the user needs to be aware of its serial number in order to address these issues. (See Appendix 2.2-1 for details.)

Advanet, Inc., of Japan, was one of the first companies to commercialize open-path gas analyzers in 1985 with the E-009 series. For many years the E-009 series was very popular and used in multiple field observations. After LI-COR introduced the LI-7500 in 2000, the number of LI-7500 users gradually increased. Currently (as of 2008), the LI-7500 is becoming the world-wide *de facto* standard instrument.

Tips!

Manufacturers do not always notify users of the latest information related to open-path gas analyzers such as version upgrades of the firmware. Users are advised to visit the manufacturers' websites every 3 to 6 months to check for the latest information on the instruments.

Tips 2.2-1

Measurement method

(1) Method of deploying an open-path gas analyzer

Two factors are considered important when an open-path gas analyzer is deployed: 1) the open-path gas analyzer needs to be deployed in such a way that it does not interfere with the measurements made by the ultrasonic anemometer thermometer, SAT; and 2) the distance between the open-path gas analyzer and the SAT should be minimized in order to minimize the loss of fluxes in the high frequency range. Often, these two factors are at odds with each other. For the deployment of an open-path gas analyzer, the characteristics of the individual observation site, e.g., the prevailing wind direction and the range of expected wind directions, also need to be taken into consideration. Therefore, no standard or formulated method of deployment exits. Here, an example of a deployed open-path gas analyzer will be introduced in order to elucidate the principles of deploying an open-path gas analyzer.

Method for deploying sensor head

Photo 2.2-1 shows an open-path gas analyzer that was deployed by a research group from the National Institute for Agro-Environmental Sciences (NIAES). If the configuration of a SAT is not rotationally symmetrical, the SAT needs to be deployed with the open section (front plane) pointed into the prevailing wind direction. When an open-path gas analyzer is deployed, it should not be placed behind the SAT structure. The open-path gas analyzer should also be mounted on the side of the SAT sensors that is downwind of the prevailing wind. In other words, the mounting position of the open-path gas analyzer needs to be selected in such a way that air parcels passing the open-path gas analyzer only occasionally flow through the SAT. This goal is most easily achieved for observation sites at which the wind direction remains relatively constant.

Tips!

It is advised that an open-path gas analyzer not be mounted behind the structure of a SAT and be mounted at some distance away from and behind the "measurement paths" of the SAT. Refer to Photo2.2-1 or Figure 3 (p.5) of the operator's manual from Campbell. (Campbell, 2006)

Tips 2.2-2

Photo 2.2-1 An example of a deployed open-path sensor (LI-7500, LI-COR). (Mase paddy flux site) A SAT (DA-600, SONIC CORPORATION, Japan) can be seen behind the open-path sensor. Because the prevailing wind direction of this site is easterly to southerly, the open section of the SAT is pointed to the south at this site. With this set up, the influence of the LI-7500 on the wind velocity measurements is small even when the wind is easterly. (Easterly wind blows from the back to the front through this photo.) Occurrence frequencies of northerly (from the back side of the DA-600) and westerly (from the direction of the LI-7500) winds are low at this observation site.

Alternatively, Campbell Scientific, Inc., US recommends that an open-path gas analyzer to be mounted horizontally underneath the measurement paths of the SAT (Campbell, 2006). With this method, the influence of the open-path gas analyzer on the wind velocity measurement is small. Therefore, this method is considered effective for SAT measurements at observation sites with a large variation in wind direction. However, when the wind direction is parallel to the measurement path of the horizontally mounted open-path gas analyzer, the sensor head of the analyzer interferes with the analyzer's measurement. This measurement interference reduces the valid range of wind directions for the open-path gas analyzer, which is considered a disadvantage of the horizontal mounting of an open-path gas analyzer. Furthermore, the frequency response characteristics of the co-spectra, i.e., fluxes, from the horizontal mounting method and the methods for correcting flux losses at high frequencies are both currently limited. (Refer to Appendix 2.2-2 for flux losses at high frequencies.)

Sensor separation distance

The ideal separation distance between the open-path gas analyzer and the SAT is 15 to 20 cm, and no larger than 30 cm. The sensor separation distance needs to be at least 15 cm. Otherwise, the influence of the sensor head on the wind velocity measurement becomes large. When the sensor separation distance is larger than 30 cm, the flux losses at high frequencies become large (particularly for an ecosystem with a small canopy height such as a grass field), and the uncertainty increases for the flux loss correction.

The sensor separation distance is defined as the distance between the center of the open-path gas analyzer measurement path and that of the SAT measurement path. When the sensor separation distance is measured, in addition to the value of the sensor separation distance, the following information needs to be recorded: the north-south as well as the east-west distance [cm] between the center of the open-path gas analyzer measurement path and that of the SAT measurement path. (Alternatively, the bearing of the position of the open-path gas analyzer can be recorded with respect to the center of the SAT measurement path.) The set of information described here will be required for correcting the flux loss at high frequencies and/or quality-controlling the data. If the centers of the measurement paths are situated at different heights, this information should also be recorded. Because of limited research on the topic, our understanding is currently limited on flux loss due to the vertical separation distance between the centers of the measurement paths, e.g., the frequency response characteristics of co-spectra and the method for correcting for flux loss. However, future research may require flux loss correction and lead to appropriate methods for correcting the flux losses due to sensors installed at different heights.

When an open-path gas analyzer is calibrated, the sensor head needs to be temporarily removed from and placed back into its deployment location. Therefore, it is recommended that the sensor head is mounted in such a manner that the position of the analyzer with respect to the SAT remains unchanged before and after the calibration. The advantages of such a mounting method include that the characteristics of flux losses remain the same between pre- and post-calibration and that the measurement of the sensor separation distance does not have to be repeated.

Method for securing the sensor head and installation angle

In addition to the cautions related to the SAT as discussed above, the method for securing the sensor head and the installation angle of an open-path gas analyzer need to be considered for its installation. Because vibrations of the sensor head at certain frequencies will influence the measurements of an open-path gas analyzer (LI-COR, 2004), the open-path gas analyzer needs to be secured in such a way as to inhibit sensor head vibrations.

Tips!

The sensor head of an LI-7500 is equipped with a mounting post and a bolt for installation (LI-COR, 2004). However, the use of the mounting post and bolt is insufficient to secure the open-path gas analyzer firmly. To ensure a secure mounting, it is advisable to use additional parts such as the crossover Nu-Rail fitting as in Campbell (2006), a cross-over plate as in Photo 2.2-1 or a U-bolt.

Tips 2.2-3

The installation angle of the sensor head of an open-path gas analyzer can be classified into 4 options: 1) vertical, 2) slightly tilted (10 to 15 degrees), 3) tilted, and 4) horizontal. The author recommends “2) slightly tilted” among these options. The advantages of a slightly tilted installation angle can be summarized as follows:

1. Flow disturbance related to the measurement by the open-path gas analyzer is small. (Accurate measurements are possible for any wind direction.)

2. Rain water can run off easily. (Little rain water accumulates on the lens that is located at the end of the measurement path.)
3. The frequency response characteristics due to path-length averaging are well understood. (For the frequency response characteristics, the sensor head can be considered to be oriented vertically in an approximate sense.)
4. If an LI-7500 is used for observation and the analyzer can be assumed to be vertically oriented, the correction formula due to instrument surface heating of Burba *et al.* (2008) is applicable. (Refer to Appendix 2.2-3 for the issue of instrument surface heating.)

The disadvantages of installing an open-path gas analyzer with a slightly tilted are the following:

5. When wind flows from the open-path gas analyzer to a SAT, the SAT measurement is disturbed. (This disadvantage can be minimized if the open-path gas analyzer is installed by taking into consideration the prevailing wind direction.)
6. When an LI-7500 that was manufactured prior to the one with serial number 0282 is used, direct solar radiation influences the measurement. (Refer to Appendix 2.2-1.)

If an open-path gas analyzer is installed vertically (option 1), rain drops tend to accumulate on the lens. If an open-path gas analyzer is installed with a tilt or horizontally (options 3 and 4, respectively), the interference of the analyzer on the SAT measurement is small if the analyzer and SAT are positioned appropriately. With these installation methods, the instrument surface heating can also be reduced. However, the frequency response characteristics of both the spectra and co-spectra from a tilted or horizontal open-path gas analyzer remain unknown, and the ability to correct flux losses at high frequencies becomes limited (Appendix 2.2-4).

(2) Method for recording output signals

When output signals are analog-recorded in voltage, the output signals may be contaminated by noise, and low-pass and/or digital filters are applied to remove the noise as necessary. For recording the data output from an LI-7500, the use of the Synchronous Device for Measurement (SDM) communication protocol of Campbell is highly recommended. Unlike analog recording, recording with the SDM communication protocol avoids the issue of noise. The SDM communication protocol also allows the simultaneous recording of the operation status of the analyzer. One of the recorded variables that represents the operation status is the Automatic Gain Control (AGC). The value of AGC changes according to the presence of objects, e.g., dirt and pollen, that are adhered to the lenses and interfere with the measurements in the measurement path. The AGC data are particularly useful for quality-controlling the acquired data.

When output signals are recorded, caution must be exercised on compensating for the time lag of the signal output. After measurements are made by the sensor head of an LI-7500, they are processed in the control box. This measurement processing requires time, which causes a time lag in outputting the data. The duration of the time lag varies according to the specified output format. The product manual for the LI-7500 (LI-COR, 2004) provides the following time lags for signal output: 0.240 seconds for signal output in voltage and 0.186 seconds for sampling with SDM and RS-232C. With the LI-7500 software, the time lag can be increased in increments of 0.0065 seconds. Consider the case in which the output signal is recorded in the SDM format with a time interval of 0.1 seconds. If the time lag is increased by 17 units (0.0065 seconds × 17 = 0.1105 seconds), the total time lag of the output signal becomes 0.297 seconds (0.186 seconds + 0.1105 seconds), which corresponds to three data values (0.297 seconds / 0.1 seconds). Therefore, if the time lag of the SAT is zero, the data from the SAT and from the LI-7500 can be synchronized (almost perfectly) by shifting the time series of data from the LI-7500 forward by three values. (The remaining slight mis-synchronization, 0.3 seconds –0.297 seconds = 0.003 seconds, is considered sufficiently small to be neglected for most sites.) To summarize, when an LI-7500 is used for observation, the time lag of the signal output needs to be adjusted according to the signal output format, the time lag of the SAT, and the data recording interval so that the total mis-synchronization within the system becomes sufficiently small.

No descriptions of the time lag of the output signals are provided in the product manuals for the E-009 or the OP-2. When these open-path gas analyzers are used, the time lag should be considered equal to zero. Alternatively, cross-correlation can be used to estimate the time lag. Calculate the cross-correlation coefficient of the output signals from the SAT and those from the analyzer as a function of the time lag. The time lag at which the cross-correlation coefficient reaches the maximum value is used as the time lag of the output signals of the open-path gas analyzer with respect to the SAT. The use of the latter approach implicitly includes a partial correction of flux losses due to the sensor separation in the along-wind direction. Therefore, when this estimation approach is adopted, caution is necessary to avoid over-correcting flux losses in the course of the flux calculation.

The time lag of the output signal influences the flux calculation significantly at sites at which the contribution of the co-spectra at high frequencies to the total flux is large, e.g., grassland. The issue of the time lag of the output signal needs to be addressed especially for those sites.

(3) Maintenance

The maintenance of an open-path gas analyzer is relatively easy. During regular visits to the observation site, it is advisable to follow the instructions below:

1. Using the display panel of the sensor and/or the data recorder, make sure that the signal output is within the normal range. When the signal output is abnormal, one of the following may be the cause of the abnormal values:
   - Dirt and/or dust accumulated on the lenses located at the end of the measurement path (see instruction 2 below)
   - Loose connections of cables or signal wires
   - Trouble with the power and voltage supplies
   - Blown fuse
   - Abnormality in the environment surrounding the control box (e.g., high temperature or water intrusion)

- Broken cables or signal wires
- Deterioration of desiccant or other chemicals (if they are in use)

In addition to the possible causes above, if an LI-7500 is used for the measurement, the sensor diagnosis information should also be checked. (When SDM is used, check "Diagnostic value". The diagnosis information can also be checked by connecting the sensor to a PC with the designated software.)

2. Clean the lenses (remove dirt and/or dust accumulated on the lenses) on the measurement paths with water and Kimwipes (Kimberly-Clark Corporation, US) or other cleaning tissues. Even when the lenses look clean, accumulated fine dirt or dust particles may be influencing the measurement. Regardless of whether dirt or dust is apparent on the lenses, it is advisable to clean the lenses regularly at a rate of once every 10days to once a month. (Refer to Appendix 2.2-5 for the effect on the measurement of dirt or dust on the lenses.) Finally, application of water repellent such as Rain-X (Pennzoil-Quaker State Company, US) on the lenses is recommended.

(4) Measurement of the absolute magnitude of CO_2 number density

The absolute magnitude of CO_2 number density (time-averaged value) is required to calculate CO_2 fluxes from the data acquired by an open-path gas analyzer. An open-path gas analyzer can measure the absolute magnitude of CO_2 number density. However, because the measurement path of an open-path gas analyzer is exposed to the atmosphere, the lenses located at the end of the measurement path can easily accumulate dirt and dust. The dirt or dust accumulated on the lenses influences the measurement of the absolute magnitude of CO_2 number density. (See Appendix 2.2-5 for reference.) Thus, if possible, it is desirable to measure the absolute magnitude of CO_2 number density (or CO_2 mixing ratio) with a closed-path analyzer. Because the measurement with a closed-path analyzer is intended for the evaluation of the time-averaged values of the absolute magnitude of CO_2 number density, an analyzer with a relatively slow response time can be used. However, make sure to select an analyzer that can provide reliable values of the absolute magnitude of CO_2 number density. If the use of a closed-path analyzer is not feasible, the use of a humidity sensor such as the HMP45 manufactured by Vaisala, Oyj., Finland can be used instead as proposed by Serrano-Ortiz *et al*. (2008). In this method, the time-averaged values of the atmospheric water vapor content obtained from the humidity sensor are compared to those obtained from the open-path gas analyzer. From this comparison, the amount of dust and dirt on the lenses is estimated, and the offset in the absolute magnitude of CO_2 number density measured by the open-path gas analyzer can be corrected.

Calibration

As discussed in the beginning of this section, the variable measured by an open-path gas analyzer is CO_2 number density [mol-CO_2m^{-3}]. On the other hand, the unit of mixing ratio [ppm] is usually used to label the cylinder that contains the CO_2 gas used for calibration. (Refer to Appendix 2.2-6.) Therefore, in order to calibrate an open-path gas analyzer, the mixing ratio of CO_2 in the calibration cylinder needs to be first converted into units of CO_2 number density with the use of the temperature and pressure within the sample cell. The obtained value of the CO_2 number density is compared to the output value from the open-path gas analyzer to determine the offset value and sensitivity of the analyzer. The calibration tube for the LI-7500, which is an accessory for the LI-7500, is equipped with a thermistor, thus the above-mentioned unit conversion for the CO_2 gas in the cylinder can be easily made using the data from the pressure meter inside the control box. (If a separate pressure meter is available, the measurement of the pressure inside the calibration tube can also be made.) If an E-009 or OP-2 is used for observation, a temperature sensor can be attached inside the calibration tube. (Alternatively, the temperature sensor can also be attached to the outside wall of the calibration tube.) The temperature measured by the temperature sensor and the pressure near the calibration tube (or a constant pressure value, e.g., 101.3 kPa) are used for the unit conversion for the concentration of the CO_2 gas in the cylinder.

Frequency of calibration is an important factor to consider. The CO_2 flux observational group of NIAES has extensive experience in using the open-path gas analyzers listed in Table 2.2-1. When all factors are considered together along with the knowledge acquired from experience, the CO_2 flux observational group recommends the following frequencies for calibration: once every month to three months for the E-009 and the OP-2; once or twice a year for the LI-7500. The change in the calibration coefficients with time for each of the three analyzers is provided in Ono *et al*. (2003) and Ono *et al*. (2007). When the user has become familiar with the calibration procedure of an open-path gas analyzer, only 5 to 6 hours are necessary to complete the entire calibration procedure including the warming-up time for the analyzer prior to calibration. In this case, the open-path gas analyzer can be taken back to the laboratory in the evening for calibration. After completing calibration during the night, the analyzer can be brought back to the observational site for re-installation the next morning. In contrast, if the user is not yet familiar with the calibration procedure, multiple attempts may be necessary to carry out the entire procedure and calibration may take up to 1 to 2 days. During the calibration period, no data can be collected in the field. Therefore, the timing of calibration should be planned in advance in order to avoid time periods during which flux data are necessary.

Cleaning of the lenses located at the end of the measurement path is at least as important as the frequency of calibration. (Refer to "Measurement Method (3) Maintenance" and Appendix 2.2-5.) The offset due to dirt or dust accumulated on the lenses is generally larger than the changes in offset and calibration coefficients of the individual analyzer, particularly for the LI-7500, thus the lenses of the analyzer need to be cleaned periodically.

Here, (1) the equipment necessary for calibration and (2) the procedure for calibration will be discussed. The discussions will assume the use of an LI-7500 and will include calibration for H_2O. Subsequently, (3) calibration of an E-009 and an OP-2 will be discussed. In this section, the sensitivity is defined as the ratio of the change in the indicated quantity (output value) to the change in the measured quantity (the value of the mixing ratio of CO_2 in the calibration cylinder). The units of sensitivity are non-dimensional or V(mol-CO_2m^{-3})$^{-1}$. In addition, the offset is defined as the value (output value) indicated at the time of zero-gas supply. The units of offset are ppm, mol-CO_2m^{-3} or volts.

(1) Equipment required for calibration

Standard gas for calibration

For calibration, three cylinders with the following concentrations of CO_2 are required: 0 ppm, i.e., zero-CO_2 gas, approximately 300 ~ 350 ppm, and approximately 500 ~ 700 ppm. (Cylinders with more than 3 different CO_2 concentrations can also be used. In this case, make sure to include cylinders with at least the following 2 different CO_2 concentrations: 0 ppm and approximately 500 ~ 700 ppm or 400 ~ 500 ppm for studies in forests.) The concentration of H_2O in the standard gas is usually zero, thus the above-mentioned cylinders with the standard gas for CO_2 can also be used as zero-H_2O gas. As for the balance gas, the use of an air balance is recommended over the use of pure nitrogen.

Tips!

CO_2 standard gas is a gas that has been certified for a specific concentration. All other gases besides CO_2 are called balance gases. Common balance gases include nitrogen (N_2 balance) and air (air balance). For CO_2 concentration measurements in the atmosphere, it is advisable to use a CO_2 standard gas in which air is used as the balance gas. This choice is recommended because the absorption characteristics of infrared radiation by the gas mixture vary according to the balance gas.

Tips 2.2-4

Zero-CO_2 and zero-H_2O gases can also be produced with chemical scrubbers. A number of chemical scrubbers are considered appropriate for producing zero gases, and their characteristics are summarized in LI-COR (2003). LI-COR (2003) recommends a combination of soda lime and magnesium perchlorate for removing CO_2 and H_2O from the air to produce zero gases. (The air needs to pass through the chemicals in the correct order: the soda lime first and subsequently the magnesium perchlorate.)

Pressure regulator

It is recommended to use a pressure regulator with two adjustment screws that can adjust the gas pressure from the cylinder to approximately 0.1 MPa (= 1.1 kgfcm^{-2} or 15 psi). Prepare tube fittings appropriate for the tubing to be used for calibration.

Tubing

Tubing that is made of fluoroethylene resin such as Teflon and is either 6 mm or 1/4 inch in the outer diameter is frequently used for calibration. Choose appropriate tube lengths to facilitate ease of use. Minimize the length of the tubing for H_2O calibration to avoid condensation inside the tubing.

Flow meter

Select a flow meter that can measure a flow rate of approximately 1 Lmin^{-1} and allows flow rate adjustment at an increment of approximately 0.1 Lmin^{-1}. A float-type flow meter is frequently used for calibration.

Dew-point generator

A dew-point generator is usually used for H_2O calibration. In the field of research flux observations, the LI-610 portable dew-point generator manufactured by LI-COR is used as the *de facto* standard dew-point generator. The LI-610 is already equipped with a floating-ball flow meter; therefore connect the LI-610 directly to the calibration tube with a length of tubing. (It is better to avoid including a flow meter between the LI-610 and the calibration tube as the inclusion of a flow meter increases the likelihood of condensation or leakage within the system.)

Other equipment

Other equipment required for calibration includes the following: the calibration tube for the LI-7500; a PC running the software for the LI-7500 analyzer, LI7500.exe (hereafter referred to as "LI-7500 software"); and a serial cable to connect the control box to the PC. When the pressure inside the calibration tube is measured, a barometer will also be required. (For this measurement, a regular barometer used for meteorological observations such as the PTB210 manufactured by Vaisala is sufficient.)

(2) Calibration procedure

The procedure for calibrating an LI-7500 that has been in operation at an observational site is explained below. Based on the purpose of individual stages of calibration, the entire calibration procedure can be roughly classified into 3 steps, which will be referred as Step 1, Step 2, and Step 3. In this subsection, precautions regarding the preparation and the entire procedure for calibration will be discussed first. Subsequently, the work sequence within each step will be explained.

Preparations and important reminders for the calibration procedure

1. If the equipment necessary for calibration can be taken out to the observational site, calibration can potentially be conducted outdoors. However, outdoor calibration is subject to changes in the external environment during the calibration and other uncertain factors that influence the calibration results. Therefore, the user is advised not to calibrate the LI-7500 outdoors and to calibrate it indoors instead by removing the sensor head and control box from the observation stand.
2. Make sure that there is no leakage at the tubing junctions when connecting the tubing to the calibration equipment. When zero-CO_2 gas is flowing through the sensor head and tubing junctions, breath on these parts to ensure there is no leakage. i.e., ensure that the CO_2 output does not change.
3. Check the AGC output on the PC when the calibration tube is not mounted on the analyzer. Subsequently, place the calibration tube on the analyzer and make sure that the value of AGC does not change. (If the mounting position of the calibration tube is inappropriate, the value of AGC will increase.) The value of AGC also needs to be checked immediately after the initiation and before the cessation of calibration gas supply to ensure that the calibration tube is not misaligned. While H_2O gas

is supplied, despite an appropriate mounting of the calibration tube, the value of AGC can increase by approximately 10 compared to the value of AGC without the calibration tube.

4. The flow rate of the calibration gas should be set to 0.5 ~ 1.0 $Lmin^{-1}$. Adjust the flow rate after the initiation of the calibration gas supply. Also make sure to check the flow rate before shutting off the calibration gas supply.
5. The CO_2 reading should stabilize in less than 5 to 10minutes after the initiation of the calibration gas supply. In the case of H_2O, 10 to 30 minutes (or sometimes longer) are required for the reading to stabilize after the calibration gas supply has been initiated. The stabilization of the H_2O reading frequently requires some time especially when zero-H_2O gas is supplied subsequent to supplying calibration gas that contains H_2O.
6. For analysis, use the data that are acquired in the last 1 to 3 minutes of the calibration gas supply and during which the output value is stable.
7. In the course of H_2O calibration, make sure that the dew-point temperature is always at least 3 to 5 °C lower than the ambient air temperature. This dew-point temperature setting is necessary to avoid condensation inside the tubing.
8. Occasionally, the output of the LI-7500 suddenly changes by a few ppm after the passage of some time (approximately 5 min to 1 hour) following the initiation of calibration gas supply. The change in the output of the LI-7500 is accompanied by a change in the cooler voltage of the LI-7500. During calibration (particularly in Step 2), closely monitor the output displayed on the PC to make sure that no sudden change occurs in the output.
9. The sensor head of the LI-7500 analyzer is internally equipped with two plastic bottles, containing soda lime and magnesium perchlorate that keep the detector free of CO_2 and H_2O. The product manual (LI-COR, 2004) recommends that the bottles be recharged with fresh chemicals once a year. After recharging, the analyzer needs to be operated for at least 4 hours in warm-up mode. It has been the experience of the CO_2 flux observational group of NIAES that the chemicals degrade at a slow rate and replacing the chemicals once every 2 to 3 years is sufficient. The group has also found that the analyzer needs to be operated in warm-up mode for 1 to 3 days to achieve a stable zero output after exchanging the chemicals.
10. After the completion of calibration, apply water repellant (e.g., Rain-X) on the lenses located at the ends of the measurement path to prevent adhesion of rain drops.

The individual steps of calibration

Step 1

The objective of Step 1 is to check the sensitivity and offset of the LI-7500 as it was operated at the observational site. The calibration gases required for Step 1 are zero gas and one or more concentrations of span gas for both CO_2 and H_2O.

Supply calibration gas to the open-path gas analyzer and check the sensor output. This procedure is performed on the analyzer while its condition is left the same as it was at the observational site, that is, before any cleaning is performed on the lenses located at the ends of the measurement path. To avoid removing the accumulated dirt and dust from the lenses, supply the CO_2 gas first and then the H_2O gas. This procedure determines the sensitivity and offset of the LI-7500 in its condition from the observational site as well as the degree of dirt and dust accumulation on the lenses. While the sensitivity drift of the analyzer is usually less than 1 ~ 3 %, thus small, the offset of the instrument can be as large as approximately 10 ppm.

Subsequently, clean the lenses with water and Kimwipes. When the lenses are completely dry, supply the calibration gas again and check the sensor output. At this time, either CO_2 or H_2O gas can be supplied first. This procedure determines changes in the sensitivity and offset of the LI-7500 itself. These changes are small under usual circumstances (sensitivity drift: less than 1 ~ 3 %; offset change: a few ppm).

Step 2

The goal of Step 2 is to modify the calibration coefficients stored in the control box of the LI-7500. This procedure is identical to the calibration procedure discussed in Section 4 “Calibration” of the product manual (LI-COR, 2004).

Because Step 2 modifies the calibration coefficients Z and S that are stored in the control box, both before and after Step 2, make sure to record the old and new values of these two coefficients either in a field notebook or on a PC in case these values are needed in the future. After recording the old values of the coefficients, supply zero-H_2O and CO_2 gases to the calibration tube. When the output stabilizes, perform zero adjustments on the H_2O and CO_2 channels with the use of the LI-7500 software. The zero adjustments are performed for H_2O first and then for CO_2. Next, a span adjustment is performed on the H_2O channel. For this adjustment, provide H_2O gas to the calibration tube from the dew-point generator. (The dew-point temperature setting should be 3 to 5 °C lower than the ambient air temperature.) When the output reaches a steady value, span the H_2O sensor using the LI-7500 software controls. Finally, the CO_2 sensor is spanned. Supply CO_2 gas of high concentration (500 ~ 700 ppm for analyzers used over farmland and grassland and 400 ~ 500 ppm for analyzers used over forests) to the calibration tube. When the output is stabilized, span the CO_2 sensor with the LI-7500 software controls.

In Step 2, zero calibration needs to be performed prior to span calibration. Because the presence of H_2O influences the CO_2 output, H_2O calibration should be performed prior to CO_2 calibration as a precaution. (The gas used for CO_2 calibration contains no H_2O, thus the order of calibration should not influence the calibration results in principle. However, a large offset may exist in the H_2O channel, thus it is recommended that calibration of the H_2O channel be performed first.)

Step 3

Step 3 consists of two sub-objectives: 1) checking the calibration coefficients stored in the control box that were modified in Step 2 (that is to check if Step 2 is finished successfully or not); and 2) performing a set of calibrations to be used as a reference in Step 1 of the next round of calibration in the future.

In Step 3, as in Step 1, the CO_2 and H_2O outputs are checked after supplying zero gas and more than one kind of appropriate span gas to the calibration tube of the LI-7500. If the calibration in Step 2 has been carried out properly, the difference between the stated value of the concentration of the calibration gas and the output of the LI-7500 will be small. (For CO_2, the difference should be smaller than 1 ppm; for H_2O, the difference in dew-point temperature should be less than 0.2 ~ 0.3 °C.)

When the calibration gas used in Step 2 is re-used in Step 3, the difference between the stated value of the concentration of the calibration gas and the output of the LI-7500 is expected to be small. However, when a calibration gas other than that used in Step 2 is used in Step 3, the difference between the stated value of the concentration of the calibration gas and the output of the LI-7500 will sometimes be large. For example, consider the case in which a calibration gas of 700 ppm is supplied in Step 2 and a calibration gas of 350 ppm is supplied in Step 3. In this case, the difference between the concentration of the calibration gas and the output of the LI-7500 can sometimes become as large as 1 ppm.

When the difference between the concentration of the supplied calibration gas and the output of the LI-7500 becomes large (as a rough guide, more than 2 ~ 4 ppm for CO_2 and more than 0.2 ~ 0.5 °C in dew-point temperature for H_2O), repeat Step 2 and Step 3.

(3) Calibration of the E-009 and OP-2

In principle, the E-009 and OP-2 do not require modification of the calibration coefficients stored in the analyzers. (While the gain of both open-path gas analyzers can be adjusted in the control box, the analyzers are usually used without adjusting the gain.) Accordingly, only the calibration procedure equivalent to Step 1 for the LI-7500 needs to be performed regularly to determine the sensitivity and offset of the analyzer. The preparations and important reminders for the calibration procedure and the procedure outlined in Step 1 for the LI-7500 are all applicable for the E-009 and the OP-2. However, the following cautions are also important.

Although calibration tubes are available as accessories for both open-path gas analyzers, the calibration tubes are not equipped to measure temperature or pressure for converting the units of the calibration gas concentration, unlike the LI-7500. Therefore, a thermocouple or a thermistor needs to be used to measure the temperature inside the calibration tube (or the temperature of the wall of the calibration tube). As for the pressure, measured values near the calibration tube are desirable, however, the use of a constant such as 101.3 kPa is acceptable as an approximation. Both open-path gas analyzers undergo changes in their sensitivities in environments with extremely low air temperatures (Miyata and Mano, 2002). When the open-path gas analyzers are used outside the temperature range stated in the product manual, the sensitivity and the temperature-dependency of the offset needs to be investigated prior to usage. (This caution is also applicable to the LI-7500.)

The product manual of the E-009 (Advanet, 1996) calls for a flow rate of about 5Lmin^{-1} for the calibration gas.

The OP-2 is equipped with a temperature sensor inside the sensor head. Temperature data can be output from the sensor, however, these data are intended to calibrate the drift of the CO_2 and H_2O outputs. Thus, it is advisable to avoid using these data as approximations of the temperature inside the calibration tube. (Use a separate temperature sensor instead to evaluate the temperature inside the calibration tube.) The product manual for the OP-2 (ADC, 2003) calls for at least 3-point calibration for H_2O as the H_2O output is expressed in a quadratic expression.

Finally, application of the calibration results to the observational data is considered. Over a period of observation, the sensitivity and offset of an open-path gas analyzer sometimes change significantly. In this case, the method of application of the calibration results to the observational data needs to be considered.

Because the change in the sensitivity of the analyzer influences the flux (co-variance) calculation, the sensitivity change cannot be taken lightly. If CO_2 number density (mixing ratio) data have been simultaneously collected with a closed-path analyzer, the time-averaged values of these data can be compared to those of the CO_2 number density from the open-path gas analyzer. The result of the comparison can sometimes be used to evaluate the temporal change in sensitivity. If no CO_2 number density (mixing ratio) data are available from a closed-path analyzer (or an evaluation of the temporal change in sensitivity was not possible from the comparison), choose either of the following methods: 1) apply the new value of the sensitivity since a particular date chosen by the investigator; and 2) adjust the data using a mathematical operation that is based on the initial and final values of sensitivity over the period under consideration. (See below.) In the former method, if an incidence such as a power outage occurred that would change the sensitivity of the analyzer, the investigator should consider adjusting only the data collected after the incidence. If no such incidence occurred, adjust the data collected after the most recent calibration or after the mid-date between the previous and present calibrations. In the latter method, two further options can be considered. In the first option, the average of the two values of sensitivity is used to adjust the collected data. In the second option, the value of sensitivity can be calculated by distributing the difference between the two values of sensitivity in proportion to the time elapsed (number of days) between the latest calibration and the one before. However, there is no obvious solution for adjusting the collected data if no information on the change of sensitivity with time is available. Determine the sensitivity to be applied for data adjustment by taking the magnitude of sensitivity change and the length of the observational period into consideration.

Changes in the offset value have no impact on the calculation of co-variance, therefore, as long as CO_2 number density (mixing ratio) has been measured additionally by a closed-path analyzer, the flux calculation will not be influenced by the change in the offset values. If no closed-path CO_2 analyzer data are available, compare the H_2O output by the open-path gas analyzer to the water vapor content measured by a separate humidity sensor. From this comparison, the temporal change in the offset value of the CO_2 data can sometimes be evaluated. (Refer to "Measurement method (4) Measurement of the absolute magnitude of CO_2 number density" or Appendix 2.2-5.) If none of the above-mentioned methods can be used, follow a procedure similar to that for adjusting data for the change in sensitivity of the open-path gas analyzer.

Tips!

If the calibration results (sensitivity and offset) change significantly over a specific observational period, calculate the flux values with both sets of calibration results to evaluate the difference in the flux values caused by the difference in calibration results. It is also advisable to plot the relationship between the calculated flux values and a meteorological factor (e.g., the relationship between solar radiation and CO_2 flux). This plot sometimes reveals a change in both the flux values and the meteorological factor after a particular time, which helps the investigator determine the time period in which the changes in the sensitivity and offset values occurred.

Tips 2.2-5

2.2.2 Measurement of fluctuating H_2O concentration by an open-path gas analyzer

The measurement of water vapor (H_2O) by an open-path gas analyzer relies on the infrared absorption characteristics of H_2O molecules for the measurement principle. One advantage of the use of this measurement principle is that it allows a simultaneous measurement of CO_2 with an interference filter that transmits radiation with particular frequencies. Accordingly, open-path H_2O/CO_2 infrared gas analyzers (referred to as an "open-path IRGA" hereafter) are currently (as of 2008) the most commonly used analyzers in the field of research flux observations. Other factors that make open-path IRGAs the number one choice for H_2O flux (i.e., latent heat flux) observations are their widespread availability and the abundance of information on using them for measurements and flux calculations.

In addition to open-path IRGAs, open-path ultraviolet gas analyzers are also open-path H_2O gas analyzers. The measurement principle of open-path ultraviolet gas analyzers is based on the ultraviolet absorption characteristics of H_2O molecules. Thermocouples are also sometimes used for measuring H_2O although they are not strictly open-path gas analyzers. However, the use of these non-IRGA instruments is not widespread, and some aspects of these instruments are not well-suited for long-term continuous observation. Except for cases with special research objectives and needs that call for the use of non-IRGA instruments, an open-path IRGA is recommended for constructing a new observation system.

Types of available analyzers

Open-path gas analyzers are the collective term for gas analyzers for which the measurement sections for the sample gas are exposed (open) to the atmosphere. Ordinarily, as the measurement principle, open-path gas analyzers utilize the absorption characteristics of particular wavelengths of radiation by gaseous molecules (e.g., H_2O and CO_2). Specifically, the infrared source situated at the end of the measurement path emits a well-defined amount of infrared radiation to a detector that is situated at the other end of the measurement path. The infrared radiation measured by the detector provides a measurement of the attenuation of the infrared radiation over the measurement path (between the infrared source and the detector). This measurement is then used to calculate the number density of gaseous molecules in the measurement path. In general, the response time of open-path gas analyzers is shorter than that of closed-path gas analyzers. Open-path gas analyzers are able to sample data at rates as high as 10 to 20 Hz, allowing accurate measurements of the fluctuating number density of gaseous molecules. However, because the measurement path is exposed to the atmosphere, the infrared source and detector of an open-path gas analyzer are subject to influences from the ambient environment. Therefore, open-path gas analyzers are not well-suited for stable and accurate measurements of the absolute magnitude of the number density of gaseous molecules.

Open-path gas analyzers for H_2O measurements can be classified into open-path IRGA and open-path ultraviolet gas analyzers according to the wavelengths of radiation used. As described in the beginning of this section, open-path IRGA are able to measure H_2O and CO_2 simultaneously and are the main gas analyzers used for flux observations at the present time. Unless there exist specific reasons for choosing ultraviolet gas analyzers, the use of open-path IRGAs recommended for H_2O flux observations. H_2O flux measurements are also possible with thermocouples. Though it is not strictly open-path gas analyzer, the methodology that involves the use of thermocouples will be introduced briefly in this section. The characteristics of each type of sensor are summarized below.

(1) Infrared gas analyzers

Refer to the section on CO_2 measurement (Section 2.2.1 “Measurement of fluctuating CO_2 concentration by an open-path gas analyzer”) for the methods of deployment, maintenance, and calibration as well as for the characteristics of open-path IRGAs. Information on commercially available open-path IRGAs can also be found in the same section.

(2) Ultraviolet gas analyzers

The measurements of open-path ultraviolet gas analyzers are based on the ultraviolet absorption characteristics of H_2O. According to the particular wavelengths of ultraviolet radiation (Lyman-alpha radiation) or the radiation source (Krypton tube) that is used for these analyzers, open-path ultraviolet gas analyzers are also called Lyman-alpha hygrometers or Krypton hygrometers. H_2O molecules absorb ultraviolet radiation more readily than infrared radiation. Therefore, the path length of an open-path ultraviolet gas analyzer can be shortened to a few cm, and the spatially-smoothed values of H_2O measured by an open-path ultraviolet gas analyzer are higher in resolution than those measured by an open-path IRGA. (The path length of the KH20 manufactured by Campbell (see next paragraph) is about 1 cm, which is one tenth to one twentieth of the path length of an open-path IRGA.) Some research requires the use of a short measurement path length, for example, for evaluating the turbulence transport and dissipation rate within a plant canopy. In this case, an open-path ultraviolet gas analyzer is frequently chosen for use. The disadvantages of open-path ultraviolet gas analyzers include the short lifetime of the radiation source and the large temporal variation of the calibration coefficients that are required for converting the ultraviolet attenuation into H_2O number density. Accordingly, open-path ultraviolet gas analyzers cannot be operated over a long time period (on the order of years) without investing a significant amount of labor. Finally, when H_2O measurements are made by open-path ultraviolet gas analyzers, corrections are required for the cross-sensitivity of H_2O and O_2 on the measurements. Details of the required corrections are discussed in van Dijk *et al.* (2003).

As of now, the KH20 manufactured by Campbell is one of the open-path ultraviolet gas analyzers that are available for purchase. The price of the instrument is about 1.1 to 1.2 million yen (available through TAIYO KEIKI Co., Ltd., Japan as of November, 2008), less expensive than the open-path IRGAs that are discussed in Section 2.2.1 "Measurement of fluctuating CO_2 concentration by an open-path gas analyzer". Therefore, the KH20 is an appropriate choice when a system needs to be constructed only for H_2O flux observations with a relatively low budget. The use of a KH20 is also appropriate for research which requires a short measurement path length as mentioned earlier. (However, the reader is reminded that a KH20 is not well-suited for long term continuous measurements.)

Refer to Section 2.2.1 for the deployment method of an ultraviolet open-path gas analyzer as it is the same as that for an open-path IRGA. For the calibration method and maintenance of ultraviolet open-path gas analyzers, refer to the product manuals.

(3) Thermocouples

Unlike open-path gas analyzers, thermocouples can be used to directly measure H_2O in the atmosphere by the sensing element of the instrument itself. There are two methods for measuring H_2O with thermocouples. One method uses a thermocouple psychrometer, and the other method uses the combination of a SAT and a thermocouple.

Measuring H_2O with a thermocouple psychrometer

A pair of dry-bulb and wet-bulb thermocouples, i.e., a thermocouple psychrometer, can be constructed with fine wires 50 ~ 100 μm in diameter (fine-wire thermocouples) to measure the air temperature. The difference in air temperature measured by the pair of thermocouples is used to evaluate H_2O concentration. A number of combinations of metals can be used to construct thermocouples. They include the combinations of copper-constantan, chromel-constantan, and chromel-alumel. Although construction of high-quality finished thermocouples may be difficult at first, thermocouples can be constructed in-house and at low cost by users. For methods of constructing thermocouples, refer to Section 3.3 "Air temperature", 森林立地調査法 (*Handbook of forest environmental survey - environmental measurement in forest-*, 1999 [in Japanese]), and 農業気象の測器と測定法 (*Instruments and measurement techniques in agricultural meteorology*, 1988 [in Japanese]). Other advantages of the use of a thermocouple psychrometer include the following: 1) the temperature measurement is highly accurate; 2) the measured value is not subject to the effect of line averaging because of the small sensing elements of the thermocouple psychrometer; and 3) a thermocouple psychrometer has little influence on the wind velocity measurement of a SAT. On the other hand, the following are disadvantages of the use of thermocouple psychrometers: 1) thermocouple psychrometers are not well-suited for long-term observations because of the significant effort required for maintenance; and 2) corrections are required on the measurements by the dry-bulb and wet-bulb thermocouples due to the difference in the response characteristics between the two types of thermocouples (Tsukamoto, 1986). Therefore, the use of thermocouple psychrometers is appropriate when an observational system is constructed for a short-term measurement at low cost.

Measuring H_2O with a thermocouple and a SAT

As discussed in Section 2.1 "Ultrasonic anemometer thermometers (SATs)", the temperature measured by a SAT is the sonic virtual temperature that includes the influence of H_2O in the atmosphere. Therefore, if the air temperature is measured by another instrument, the concentration of H_2O in the atmosphere can be calculated from the difference between the sonic virtual temperature and the measured air temperature. The air temperature can be measured by tungsten resistance wires, platinum wires, or thermistors as well as 25 ~ 50 μm diameter thermocouples. In theory, as long as the sonic virtual and actual air temperatures are measured with high accuracy, H_2O fluxes can also be measured accurately. The present method has been adopted for short-term observational studies (e.g., Hanafusa *et al.*, 2005). However, no long-term observational study (of more than a few months) based on this method has been reported in the literature. In some cases, H_2O fluxes estimated from the difference between the sonic virtual and actual air temperatures differ from those estimated from other methods (e.g., Gunji *et al.*, 2008; Matsuoka and Hayashi, 2008). The combined use of a SAT and a thermocouple or another temperature sensor for the estimation of H_2O fluxes is currently under investigation and development. Thus, the present method cannot be recommended as a method for H_2O flux measurements at the present time (as of 2008).

2.2.3 Recent progress in addressing the effect of surface heating of open-path analyzers as of 2011

Both the knowledge and technology of open-path analyzers have progressed remarkably. Three years have passed since this chapter was initially prepared in 2008. In the meantime, three new models of analyzers that have overcome measurement difficulties, specifically the effect of instrument surface heating on the CO_2 flux measurement, have been brought to market and are available for purchase today (2011). In this newly added subsection, the recent progress in addressing the effect of the surface heating of an open-path analyzer will be briefly described, and the three new models together with their individual characteristics will be introduced.

As discussed in Appendix 2.2-3, the effect of surface heating of an open-path analyzer is an issue in which the open-path analyzer becomes a heat source, creating errors in the CO_2 flux measurements due to errors in the estimate of the sensible heat flux. Specifically, the effect of instrument surface heating causes the sensible heat flux measured within the measurement path of the open-path analyzer, H_{op} [Wm^{-2}], to deviate from that measured by a SAT, H [Wm^{-2}]. The presence of this deviation ($\Delta H = |H - H_{op}|$) is becoming commonly recognized in the field of flux observation (refer to Appendix 2.2-7) as a result of past research findings including: 1) downward CO_2 flux observed by open-path analyzers even during periods with no photosynthetic activity (Harazono *et al*., 2000); 2) results based on comparisons of CO_2 fluxes observed by open-path analyzers to those observed by closed-path analyzers (H does not have to be taken into consideration) (e.g., Hirata *et al*., 2005); and 3) findings from measurements of air temperature fluctuations within the measurement paths of open-path analyzers (e.g., Grelle and Burba, 2007; Ono *et al*., 2008). An equation based on an instrument surface heat balance analysis has been proposed to evaluate ΔH, that is, as a correction method, although it is limited to a specific open-path analyzer (LI-7500) (Burba *et al*., 2008; Heusinkveld *et al*., 2008). The correction method proposed by Burba *et al*. (2008) is intended to be versatile so that it can be easily applied to previously-acquired data as well as newly-acquired data. However, the equations used in this method were derived for vertically deployed open-path analyzers, and there remain some uncertainties arising from some of the simplifying assumptions. While the correction method proposed by Heusinkveld *et al*. (2008) requires iterative calculations, it takes into account the latent heat term which evaluates the amount of water condensed on the lenses at the ends of the measurement path, the difference between the temperature of the measurement path of the SAT and that of the open-path analyzer, and other factors. This method is applicable for open-path analyzers that are deployed either horizontally or vertically. (However, the method is not applicable to analyzers which are deployed with a tilt, a commonly adopted deployment style for flux observations.) In the session titled “Barriers in Flux Measurements” at AsiaFlux Workshop 2009, discussions were held on the effect of instrument surface heating with Dr. Burba, one of the investigators who have proposed a correction method for this effect. In this session, it was brought up that the correction term may underestimate the necessary correction in a low-temperature environment (a brief summary of the content of the discussion is reported in Ohkubo *et al*., 2009). In the Workshop, a simulation study was presented, indicating that the correction term of Burba *et al*. (2008) overestimates the necessary correction in high wind speed conditions (Ono *et al*., 2009). Currently, there is no agreement on the method for evaluating ΔH. Amiro (2010), for example, calculated the cumulative CO_2 flux for two cases, that is, using the correction term as is and using the correction term reduced by 50 %, and compared the two values. Furthermore, the effect of instrument surface heating, that is, the difference between the air temperature within the measurement path of an open-path analyzer and the actual air temperature becomes large in a low temperature environment. (Burba *et al*. (2005) showed that the temperature difference can become 4 °C or 10 ~ 12 °C at an air temperature of –10 °C.) Therefore, in practice, the correction method of Burba *et al*. (2008) is applied only to data colleted at air temperatures below 0 °C (or below –10 °C), or alternatively, missing values are assigned to these data (Mkhabela *et al*., 2009; Amiro, 2010). As discussed above, it has become commonly acknowledged that conventional measurements with open-path analyzers are subject to the effect of instrument surface heating, however, this issue is being handled on a trial and error basis as of today (2011).

In parallel with the efforts to clarify the effect of instrument surface heating by researchers, efforts have been made by manufacturers to address the effect by improving existing open-path analyzers. In order to address the effect of instrument surface heating (non-zero ΔH), the following three measures are considered effective, and three new models were brought to market in 2010 based on the second and third measures.

The first measure, instead of aiming to minimize or eliminate ΔH, calculates CO_2 flux from the directly measured value of H_{op} rather than the value of H. Grelle and Burba (2007) placed a fine-wire thermometer of 0.1 mm diameter (fine-wire Platinum Resistance Thermometer) on one of the support rods of the measurement path of an LI-7500 in order to measure the air temperature fluctuations within the measurement path. The CO_2 flux calculated with the sensible heat flux from this thermometer (H_{op}) agrees well with that evaluated from a closed-path analyzer (LI-6262, LI-COR), suggesting that this measure is effective for addressing the effect of instrument surface heating. This measure, which utilizes a fine-wire thermometer (or a thermocouple), is applicable for other conventional open-path analyzers in addition to the LI-7500. Furthermore, the thermometer can be installed by an investigator, and the system can be constructed at a relatively low cost. However, this measure is not well-suited for stable continuous observations extending over a long period as, being made of fine-wires, the sensing element of the thermometer deteriorates with age and is easily damaged by high speed winds and rainfall. Such disadvantages of this measure are probably among the reasons that no analyzer models based on this measure are commercially available at the present time.

The second measure is based on the notion of minimizing ΔH as much as possible. ΔH is generated as a result of the open-path analyzer being a heat source, which is attributable mainly to heat generation from the interior of the analyzer; or; longwave or shortwave radiation striking the analyzer, or both. While heating by the former cause can be reduced by cutting down the power consumed by the analyzer, heating by the latter cause (radiation) can be reduced by adjusting the analyzer configuration (specifically, for example, by cutting down the area that receives radiation). With this in mind, LI-COR has produced the LI-7500A as a successor to the LI-7500. The LI-7500A is equipped with an internal temperature setting function, allowing the temperature to be set either at 5 °C or 30 °C according to the air temperature (LI-COR, 2011a). By adjusting the temperature setting appropriately for summer, winter, and other seasons, the analyzer can be operated with a power consumption of 12 W in the normal air temperature range (–20 to 40 °C). (The analyzer can also be operated at a minimum power consumption of 8 W, depending on the conditions. For details, contact the distributors.) Campbell has developed an open-path analyzer, the EC150, which can be used together with the CSAT3, the SAT available from the same corporation. Operation of the EC150 requires low power consumption (4.1 W at a temperature of 25 °C). The analyzer outputs measured values which have been corrected for the temperature change inside the analyzer. Optically, the analyzer is designed to reduce the radiation effect. Because the analyzer is also slim, it causes less disturbance to the wind velocity field, thus the sensor separation distance between the SAT and the analyzer can be reduced. (The sensor separation distance is 6 cm when used together with the CSAT3.) When CO_2 flux is evaluated with an open-path analyzer, high frequency flux loss (see Appendix 2.2-2) is generally most attributable to sensor separation. Therefore, the slimmer analyzer not only reduces the effect of instrument surface heating on the flux measurement, but also reduces the magnitude of the flux loss correction term (that is, reduction of uncertainties). Furthermore, the EC150 is equipped with a feature to enhance water vapor evaporation subsequent to rainfall and diminish water condensation on the lenses at the ends of the measurement path with the use of heaters. This feature reduces the occurrence of missing values in the data acquired by the analyzer.

Finally, the third measure addresses the effect of instrument surface heating without the need to use *H* in the process of CO_2 flux calculations. *H* is the temperature fluctuation term that is required in the mass conservation equation for dry air (Webb *et al*., 1980) and does not have to be considered for closed-path measurements because air temperature fluctuations become attenuated in the course of drawing the sample air. (However, because the degree of attenuation is influenced by factors such as tube configuration, tube length, and drawing rate, the combination of these factors needs to be selected appropriately. For details, refer to Clement *et al*., 2009). LI-COR has created a new product, the LI-7200, by covering the measurement path of the LI-7500A with a PVC hood, which is low in temperature conductivity and allows little water to adhere, and thus converting the instrument into a closed-path analyzer. With the combined use of an LI-7200, a pump exclusive for the LI-7200, and a flow rate control unit, CO_2 flux can be calculated using the calculation procedure for closed-path analyzers, that is, without using *H*. Conventional closed-path analyzers tend to be complex in terms of the configuration of the system because they are required to be installed indoors or in shelters to address the influence of rainfall and changes in the surrounding environment (particularly temperature). However, the open-path analyzer LI-7500A was adopted for the basic measurement component of the LI-7200. Because the pump and flow rate control unit of the analyzer are also designed to be weather-resistant, despite being a closed-path analyzer, the LI-7200 can be deployed outdoors. The design of the LI-7200 reduces missing data during a rainfall event, and as reported by Nakai *et al*. (2011), it also allows evaluation of the pressure correlation term, which contributes to the CO_2 flux (Webb *et al*., 1980; Lee and Massman, 2011). These features are advantages of the LI-7200. However, caution is necessary because water vapor (H_2O) fluctuations, in a similar manner to air temperature fluctuations, become attenuated in the process of drawing sample air. Because the suction tube of the LI-7200 is short, the attenuation of water vapor fluctuations inside the tube is smaller for this model than for other models of closed-path analyzers, that is, approximately 10 % of the signal is attenuated (LI-COR, 2011b). Nonetheless, this value cannot be neglected, and adequate corrections are necessary for the attenuated water vapor fluctuations. Incidentally, Campbell initiated the sale of a closed-path analyzer, the EC155, which possesses features similar to those of the LI-7200.

As discussed above, the measurement theory and hardware technology in the field of CO_2 flux measurements with an open-path analyzer are in the process of advancement. Therefore, users need to pay attention to announcements from manufacturers as well as published papers so that newly acquired knowledge can be incorporated into ongoing observations.

Appendix 2.2-1: Serial number-specific characteristics of the LI-7500 (LI-COR)

Ever since the LI-7500 became commercially available in 2000, LI-COR has been continuously modifying and improving the product. Therefore, precautions are necessary at the time of calibration and measurement for LI-7500 with certain serial numbers. These precautions are briefly summarized below. Because the product will likely continue to be modified in the future, it is advisable to visit the web site of LI-COR regularly to check the latest information.

(1) For all serial numbers

Upgrade the firmware for the control box (LI-7500 Instrument Embedded Software), the PC software (LI7500.exe), and obtain the latest product manual for the LI-7500. The latest versions (as of Nov. 2008) of the firmware, PC software and product manual are Ver. 3.0.1, Ver. 3.0.2, and Rev. 4, respectively.

(2) LI-7500s manufactured prior to serial number 75H/B-0282

When an LI-7500 manufactured prior to the one with serial number 75H/B-0282 is exposed to direct solar radiation, it affects the ends of the paths of the analyzers and changes the output (LI-COR, 2002). To avoid this effect, the sensor head of the LI-7500 needs to point north in the northern hemisphere and also needs to be tilted according to the latitude of observation. For example, for an observation at 35°N, tilt the sensor head by about 35 degrees to the north. For an observation at 40°N, tilt the sensor head by about 30 degrees to the north.

(3) LI-7500s distributed earlier than around July 2003

The firmware for the control box with version numbers Ver.1.0.0 ~ 2.0.4 is used for LI-7500s that were distributed earlier than around July 2003. The time lag of the output signal programmed in the firmware is different from that given in the product manual. (LI-COR refers to this discrepancy in the time lag as timing error.) This timing error can be eliminated by upgrading the firmware to Version 3.0.0 or later versions.

(4) LI-7500s manufactured after serial number 75H/B-0370

As a result of improvements in the main circuit in the control box, LI-7500s manufactured after the one with serial number 75H/B-0370 can be used at low air temperatures (down to –40 °C). As long as the calibration coefficients can be transferred properly, LI-7500s can be used for measurements even if the serial numbers of the sensor head and the control box do not match. However, the coefficients determined for a combination of the main circuit of a control box manufactured before the above-mentioned improvement and a sensor head cannot be used for a combination of the main circuit of a control box manufactured after the improvement and a sensor head, and vice versa. Therefore, when the sensor head that was used with the old-version (new-version) control box is transferred to the new-version (old-version) control box, calibration needs to be performed for the new combination of sensor head and control box. LI-COR recommends that calibration be performed, prior to the measurements, on the sensor head combined with the control box when the serial numbers differ between the sensor head and the control box (even when the type of control box itself remains the same before and after the change in combination). Refer to pp. 3–18 ~ 3–20 of the product manual for the LI-7500 (Rev. 4) (LI-COR, 2004) for details on changing the sensor head.

Appendix 2.2-2: High frequency flux loss

When the measurement sensor for the vertical wind velocity and that for a scalar quantity (CO_2 in the present section) are separated by some distance, the sensor separation changes the cospectral shape (frequency response characteristics). Numerous observations and studies have been conducted on the effect of the sensor separation in the horizontal plane (horizontal direction) on the cospectral shape, and satisfactory methods for correcting the change in the cospectral shape have been established (e.g., Moore, 1986; Massman, 2000). However, the influence of vertical separation between the two sensors on the frequency response characteristics is not fully understood. When flux loss due to the vertical separation of the sensors is corrected, a technique such as the band-path method which is often applied for flux measurement with a closed-path analyzer (e.g., Watanabe *et al.*, 2000) should be adopted. The methods for correcting flux loss due to the sensor separation described here are discussed in the analysis edition of the present manual.

Appendix 2.2-3: The influence of heating by the open-path gas analyzer on flux calculation

When CO_2 fluxes are calculated using data collected by an open-path gas analyzer, the correction term for air density fluctuations (dry air flux) needs to be evaluated (Webb *et al.*, 1980). (For details of the Webb correction, refer to the analysis edition of the present manual.) The Webb correction requires evaluation of air temperature fluctuations within the measurement path of the open-path gas analyzer (sensible heat flux, H_{op}). In the past, H_{op} was assumed to be the same as the sensible heat flux measured by the SAT. However, in recent years, it has been reported that the difference between the two sensible heat fluxes ($\Delta H = |H_{op} - H|$) cannot be neglected for the Webb correction (e.g., Burba *et al.*, 2008; Ono *et al.*, 2008). The magnitude of the introduced error depends on the magnitude of ΔH not that of H. (That is, the issue arises regardless of the absolute magnitude of H.)

The non-zero value of ΔH originates from the open-path gas analyzer itself being the source of heating of the air within the measurement path. The instrument can be heated due to its internal electronics or by solar radiation. Burba *et al.* (2008) proposed a correction method for ΔH for vertically-deployed LI-7500s. Thus, the correction method is not applicable for LI-7500s that are deployed other than vertically. The same method is also not applicable to other open-path gas analyzers although they are also likely subject to the heating issue. The issue of an open-path gas analyzer being the source of heating remains under investigation as of today (2008), and journal articles associated with the topic continue to be published (e.g., Heusinkveld *et al.*, 2008.) Thus, investigators are advised to keep up with the latest research trends and future announcements by the manufacturer.

Appendix 2.2-4: Issues associated with horizontally deployed open-path gas analyzers

The value of the CO_2 number density measured by an open-path gas analyzer is that within the measurement path. Accordingly, when the measurement path length is 20 cm, CO_2 number density variations occurring at a length scale smaller than 20 cm are averaged. When an open-path gas analyzer is deployed vertically, CO_2 number density variations occurring at a length scale smaller than 20 cm in the vertical direction are averaged. Numerous studies have been conducted on the smoothing of CO_2 number density fluctuations measured by open-path gas analyzers mounted vertically, thus the smoothing effect can be evaluated and/or corrected. When an open-path gas analyzer is deployed horizontally, CO_2 number density variations occurring at a length scale smaller than 20 cm in the horizontal direction are averaged. In the vertical direction, CO_2 number density variations occurring only at very small length scales are averaged. For this case, there exists little research in the literature on the smoothing of CO_2 number density fluctuations, and no appropriate method is currently available for evaluating and/or correcting the smoothing effect.

Appendix 2.2-5: Influence of dirt and dust accumulated on the lenses of the open-path gas analyzer on CO_2 number density measurements

When dirt and dust accumulate on the lenses of an open-path gas analyzer (LI-7500), the CO_2 and H_2O outputs are offset (Serrano-Ortiz *et al.*, 2008). According to Serrano-Ortiz *et al.* (2008), when the outputs with dust-induced offsets are used to calculate fluxes, the errors on the calculated fluxes become large when evaluating the long term (e.g., yearly) cumulative flux values. To minimize such errors, the following actions are considered effective: 1) measure the absolute magnitude of CO_2 number density (mixing ratio) with a closed-path analyzer; 2) compare the H_2O output from the open-path gas analyzer to that measured by a humidity sensor. Apply the result of this comparison to correct the CO_2 output; and 3) clean the lenses at the end of the measurement path regularly. Although the discussions of Serrano-Ortiz *et al.*(2008) are strictly valid only for LI-7500s, it is likely that dirt and dust on the lenses of other open-path gas analyzers also induce offsets in the CO_2 and H_2O outputs. Thus, the above-mentioned actions may be necessary when data are collected by other open-path gas analyzers.

Appendix 2.2-6: Density and mixing ratio

CO_2 mass density is defined as the mass of CO_2 that is included in a unit volume of air. CO_2 mixing ratio is expressed as the ratio of CO_2 mass density, ρ_c [kgm^{-3}], to dry air density, ρ_d [kgm^{-3}], that is,

$$\frac{\rho_c}{\rho_d} = \frac{m_c}{m_d}\frac{p_c}{(p-e)} \quad \text{(A2.2-1)}$$

where m_c : molecular weight of CO_2 [kgmol^{-1}], m_d : molecular weight of dry air [kgmol^{-1}], p: atmospheric pressure [Pa], e: water vapor pressure [Pa], p_c: partial pressure of CO_2 [Pa]. The partial pressure of CO_2, p_c is related to CO_2 concentration as $p_c = \rho_{cc} p \times 10^6$, where ρ_{cc} is the CO_2 concentration [μmolmol^{-1}].

Appendix 2.2-7: Literature which reports a negligible effect of instrument surface heating on open-path analyzer measurements

Some literature such as Giasson *et al*. (2006) and Haslwanter *et al*. (2009) reported that the effect of instrument surface heating on the flux measurements by an open-path analyzer is negligibly small. At the observation site of Giasson *et al*. (2006), winter CO_2 flux indicating absorption of CO_2 by the ecosystem, which is caused by the effect of instrument surface heating, was not observed. Amiro (2010) suggested that high wind speeds might have reduced the effect of instrument surface heating, leading to the results observed by Giasson *et al*. (2006). Specifically, concurrent with the cooling of the instrument directly by the wind, H_{op} / H_{body}, the ratio of H_{op} (see Appendix 2.2-3) to the sensible heat flux generated at the instrument surface, H_{body} [Wm^{-2}], might have decreased with increasing wind speed, an effect reported by Ono *et al*. (2009).

2.3 Closed-path CO_2 gas analyzers

The eddy covariance method that uses a closed-path CO_2 gas analyzer (closed-path gas analyzer hereafter) was developed when no open-path CO_2 gas analyzers were yet available for long-term stable CO_2 measurements (e.g., Leuning and Moncrieff, 1990; Leuning and King, 1992; Suyker and Verma, 1993). The eddy covariance method that is based on the measurements from a closed-path gas analyzer evaluates CO_2 fluxes from the wind velocity fluctuations observed by an ultrasonic anemometer thermometer and fluctuations of the atmospheric CO_2 concentration observed by a closed-path gas analyzer. In the meantime, the LI-7500 (LI-COR, Inc., US), which was discussed in Section 2.2 “Open-path CO_2/H_2O gas analyzers”, has become commercially available and has been used widely. As a result, the number of observational sites which newly adopt a closed-path gas analyzer for the eddy covariance method is probably decreasing. On the other hand, the use of a closed-path gas analyzer provides the following advantages (AsiaFlux Steering Committee, 2007): 1) long-term stable measurements can be made; 2) calibration can be automated; and 3) the magnitude of the density fluctuation correction is small. Advantage 1) can be achieved because the sensing element of a closed-path gas analyzer is protected from direct exposure to the atmosphere and rainfall. Automated calibration (advantage 2) is possible with a closed-path gas analyzer because of its automatic switch-over function which allows a standard gas to flow into the flow path of the analyzer. The disadvantages of a closed-path gas analyzer include: 1) its cumbersome and complex measurement system; and 2) attenuation of fluctuations of CO_2 concentration during the sampling procedure. Under some observational conditions, the use of a closed-path gas analyzer may be better-suited for the eddy covariance method than the use of an open-path gas analyzer (Ono *et al*., 2007). Thus, it may be to the investigator’s advantage to acquire an understanding of the use of closed-path gas analyzers for the eddy covariance method, so that this technique becomes an option for measuring CO_2 fluxes.

The discussions in this section will mainly focus on CO_2 concentration measurements by closed-path gas analyzers although recently designed closed-path gas analyzers are capable of measuring both CO_2 and H_2O concentrations in the sampled air.

(1) Summary of the air sampling system that includes a closed-path gas analyzer

Fig. 2.3-1 shows a schematic of an air sampling system that includes a closed-path gas analyzer. A photo of the air sampling system in Fig. 2.3-1 is shown in Photo 2.3-1. In flux measurements with a closed-path gas analyzer, CO_2 concentration measurements are made on the sample air that is collected at the measurement point and sent to the analyzer through the tubing. The sample air is drawn into the analyzer with a pump. The length of tubing between the measurement point and the pump is determined based on the deployment location of the analyzer.

Flow path of sampled air

Regarding the flow path of sampled air (see Fig. 2.3-1), sampled air is first drawn in by a pump from the measurement point (negative pressure). The moisture in the pumped air is removed with a membrane dehumidifier made of resin. After the flow rate of the dried air has been regulated by a mass flow controller, the dried air is sent into the sample cell of the CO_2 analyzer (e.g., LI-6262 or LI-7000 manufactured by LI-COR). Inside the sample cell, CO_2 concentration of the dried air is measured, and the dried air is released out of the analyzer. In the system shown in Fig. 2.3-1, the moisture in the sampled air is removed. However, when H_2O concentration is simultaneously measured for evaluating the moisture flux, no moisture is removed from the sampled air. In this case, omit the dehumidifier shown in the schematic of the sampling system of the closed-path gas analyzer (Fig. 2.3-1) and directly bypass the dehumidifier with a tube. When no dehumidifier is used, caution is necessary as the likelihood of condensation within the sampling system increases according to the temperature and pressure changes within the pathway of the sampling system.

The suction flow rate for air sampling depends on the tubing length, tubing diameter, and the pump capacity. The air flow rate through the system after the pump is determined primarily by the maximum flow rate allowed by the CO_2 analyzer. For example, the maximum flow rate of the LI-6262 is 10 $Lmin^{-1}$ (LI-6262 manual, LI-COR) while no such value is set for the LI-7000. (The LI-7000 manual states that its maximum flow rate is unlimited.) In Fig. 2.3-1, the rate of the sampled air flow through the system after the pump is set to 2.0 $Lmin^{-1}$ in order to enhance the efficiency of the moisture removal by the membrane dehumidifier. Depending on the system configuration, the air discharge rate out of the pump can sometimes be increased to a value much larger than the maximum flow rate allowed by the CO_2 analyzer. One of the methods to achieve such air discharge rates out of the pump is called sub-sampling (Refer to Suyker and Verma, 1993, and Tips 2.3-13.) In this method, excess flow is vented out of the air sampling system between the pump and the CO_2 analyzer. When this method is utilized, a large suction flow rate can be achieved in the flow-path between the air inlet and the pump. As a result, the time lag between the air sampling and the output of the changing CO_2 concentration can be reduced.

The use of a mass flow controller is recommended for controlling the flow rate of the sampled air although a flow meter that is equipped with a flow rate control function can also be used for this purpose. A mass flow controller not only allows highly stable flow rate control, but can also suppress pressure fluctuations due to pump pulsation.

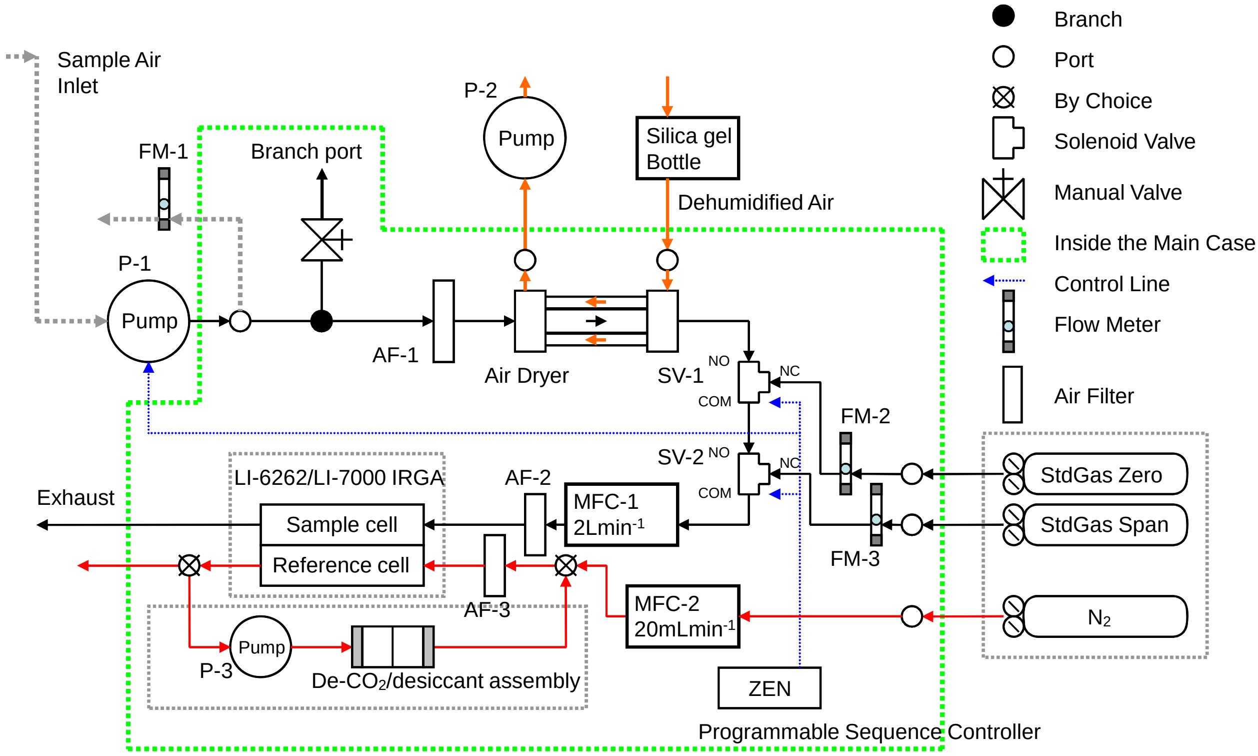

Fig. 2.3-1 An example of an air sampling system that includes a closed-path CO_2 gas analyzer.
(Figure: Ohtani *et al*., 2001, partially modified)

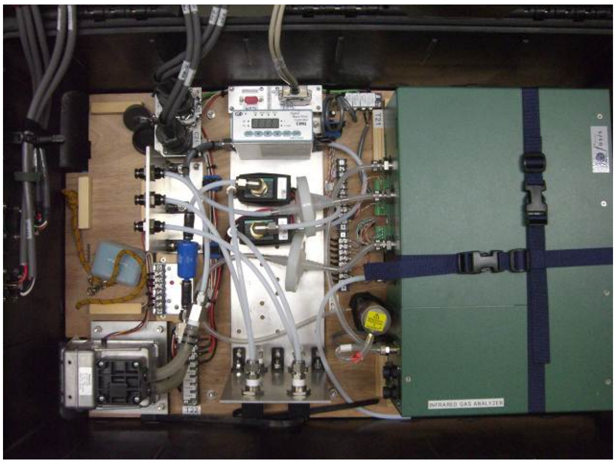

Photo 2.3-1 The air sampling system that includes a closed-path gas analyzer from Fig. 2.3-1.

Tips!

Dust generated from the pump within the air sampling system as well as insects and dust in the air can accumulate in the interior of the system piping and the cell of the CO_2 analyzer. To keep the system and cell interior free from dust and insects, the use of an air filter is recommended. For better results, the air filter should be placed at the inlet of the suction tube, immediately after the pump, and immediately before the CO_2 analyzer. The air filters that come with CO_2 analyzers manufactured by LI-COR are PTFE membrane filters with a pore diameter of 1 μm. Because similar filters are commercially available, the investigator can pick any alternatives to the LI-COR filters that can be easily handled (e.g., filters manufactured by Toyo Roshi Kaisha, Ltd, Japan.).

Tips 2.3-1

Tips!

When moisture is removed from the sampled air, H_2O concentration in the air cannot be monitored and moisture fluxes cannot be calculated with the closed-path gas analyzer. Advantages of moisture removal include the elimination of the need for the WPL correction and a reduction in the accumulation of dirt inside the sample cells. On the other hand, because the sample cells of the LI-7000 can be removed and cleaned, the analyzer can be used for long-term measurements without removing moisture from the sampled air.

Tips 2.3-2

Reference cell

Closed-path gas analyzers (LI-6262or LI-7000) evaluate the CO_2 concentration (or H_2O concentration) of the sampled air from the difference between the infrared radiation absorbed by the air in the sample cell and that absorbed by the air in the reference cell. Therefore, when the absolute magnitude of the CO_2 concentration is sought, the reference cell needs to be filled with CO_2-free gas (LI-6262 manual, LI-COR)

There are two major methods to keep the reference cell free from CO_2. (Refer to Fig. 2.3-1.) In the first method, gas free of CO_2 and H_2O (e.g., pure nitrogen) is flushed into the reference cell. In order to keep the cell constantly filled with nitrogen gas, the gas has to be supplied into the cell continuously. However, only a small flow rate is required for the gas supply. In Fig. 2.3-1, the flow rate is set to 20 $mLmin^{-1}$ as an example. The second method uses chemicals (LI-6262 manual, LI-COR). In the LI-6262, soda lime and magnesium perchlorate are used to produce air free of CO_2 and H_2O. This procedure is as simple as adding bottles containing the chemicals directly to the inlets and outlets of the reference cell. Though replacement of the chemicals may require some effort, the present method is a simple and convenient one for short-term measurements and for sites into which the transportation of cylinders of standard gas is not easily feasible. In the case of the LI-6262, if observations are made only for CO_2, the second method requires only the addition of the chemical bottles to the reference cells. However, if simultaneous observations of H_2O concentration are also required, a pump-induced forced circulation is necessary (LI-6262 manual, LI-COR). In the LI-7000, air free of CO_2 and H_2O is produced with similar chemicals, i.e., soda lime (or Ascarite) and magnesium perchlorate (or Drierite). The air within the reference cell can be circulated by the pump housed inside the LI-7000 (LI-7000 manual, LI-COR).

Tips!

While both the use of chemicals and a reference gas (CO_2 and H_2O free gas) come with advantages and disadvantages, these methods require replacement of either gas cylinders or chemicals. Gas cylinders need replacement when they run out, and chemicals need replacement when their effect wears out. (Make sure to replace the gas or chemicals *before* the gas runs out or the chemicals wear out.) The interval for the gas replacement can be extended with the use of a large gas cylinder. Although the appropriate interval for chemical replacement depends on the conditions under which the analyzer is used, manufacturers recommend a week for the interval. Our past experiences suggest that the chemicals actually last for 2 weeks to a month depending on the ambient conditions of the analyzer.

Tips 2.3-3

(2) Solenoid valves

One of the advantages of a closed-path analyzer is that the analyzer can be automatically calibrated. For the automatic calibration, the flow path of the sampled air needs to be branched to create flow paths for the calibration gas. (Refer to Fig. 2.3-1.) These flow paths are often created with the use of solenoid valves, which can be opened and closed by providing electric voltage (electric current). Furthermore, the use of three-way valves as in Fig. 2.3-1 is recommended. The three-way valves are equipped with three ports: COM, NO (normal open), and NC (normal close). When no voltage is supplied (no electric current), the COM and NO ports are connected. When voltage is supplied, the COM and NC ports are connected. When three-way valves are used, connect the COM port to the tubing that leads to the analyzer, the NO port to the tubing that originates from the sample air inlet, and the NC port to the tubing that leads to the calibration gas. When two kinds of calibration gas (i.e., zero gas and span gas) are used for calibration, connect two three-way valves in series with the COM port of the upstream valve connected to the NO port of the downstream valve. For steady sampling of atmospheric air, no electric current is sent to the valves. In this state, air that is taken in from the sample air inlet is drawn through the pump into the analyzer. In order to draw in calibration gas, supply electric current to the valve which is connected to the gas to be drawn in. Then, the NC port of the valve to which electric current has been supplied opens and calibration gas flows into the analyzer, and the NO port closes, which shuts off the air flow from the sample air inlet. If zero gas and span gas (two-point calibration gases with two different CO_2 concentrations) are drawn through the system with this procedure, the analyzer can be calibrated. In the case of automated calibration, the solenoid valves are controlled automatically with a PC or a data logger. Check the data from the time during which calibration gas was flowing and use the calibration data for data calculations.

Tips!

The prices of solenoid valves vary according to the material of their main bodies. Fluorine resin is chemically stable and weather resistant. Therefore, when the valves are used for measuring reactive gaseous constituents or for continuously flowing atmospheric air, fluorine resin material such as Teflon is frequently used for valve components. In terms of chemical reactivity, CO_2 is only weakly reactive to many materials. Therefore, when solenoid valves are used for measurements of CO_2, valves with gas contact parts made of metal can be used. When selecting solenoid valves for use, it is also desirable to select those of an appropriate size with respect to the flow rate. Refer to “orifice size” and/or “valve flow coefficient” in catalogs as a guide for selecting an appropriate size. The bigger the values of these variables, the larger the flow rate that the valves can accommodate. On the other hand, large valves require large operating power, and their inner volumes are large. Because of their large inner volumes, the displacement efficiency of large valves at the time of flow-path switchover is low, which needs to be taken into consideration for selecting the size of valves to be used for measurements. Furthermore, solenoid valves are available in AC and DC types and also in a number of voltage ratings, thus the investigator should select appropriate valves according to the power source of the measurement system.

A variety of solenoid valves are available not only in different materials but also with different numbers of valves (2-way and 3-way) and different combinations of NO and NC, thus it is suggested that the investigator order catalogs from the manufacturers. While a number of manufacturers produce solenoid valves, the author frequently uses those manufactured by CKD Corporation, Japan. In addition to CKD, solenoid valves are available from TAKASAGO ELECTRIC, INC., Japan; SMC Corporation, Japan; and KOGANEI CORPORATION, Japan.

Tips 2.3-4

(3) Pumps (characteristics and structure)

While a large number of pump structures and types are available, diaphragm pumps which are frequently used for flux observations will be discussed below. In a diaphragm pump such as those manufactured by Enomoto Micro Pump Mfg. Co., Ltd., Japan, fluid is extracted and delivered with the use of intake and exhaust valves that work in conjunction with a rubber diaphragm. Two pump drive systems for diaphragm pumps are motor-based and electromagnetic-based types. Because larger flow rates and higher pressures can be achieved by motor-based diaphragm pumps than by electromagnetic-based diaphragm pumps, the use of motor-based diaphragm pumps is recommended for measurements with a closed-path system. A motor-based diaphragm pump sharply reduces the volume of the pump chamber by flexing a diaphragm. At the pump inlet, a one-way valve is attached so that it allows air to flow only in the direction of the pump chamber. At the exhaust outlet, a valve is attached to allow the air to flow only out of the pump chamber. Thus, these valves ensure that the air flows only in a given direction in response to the flexing motion of the diaphragm. Because there exists no mechanical sliding component at the interface between the fluid (air in the present case) and the portion of the pump that meets the fluid, no fluid leaks out of the pump, which is considered an advantage of diaphragm pumps. Diaphragm pumps are available for a number of driving voltages (voltage ratings); therefore, select one for use according to the circumstances of the power source available at the field site of interest.

Brushes are used for electric contacts inside many of the DC motors that are used for generic mini-pumps. This type of pump frequently produces electronic noise and can fail as a result of brush abrasion when operated continuously over a long period. If a DC-driven pump is used, it is suggested that a brushless DC motor be used provided such an option is available.

A diaphragm pump due to its structure tends to induce flow rate pulsation. Pressure variations that result from the flow rate pulsation sometimes affect the measurement values of the gas analyzer. The following measures can be taken to mitigate the effect of the flow rate pulsation. First, when the pump is placed upstream of the analyzer, resistance such as a mass flow controller or a membrane dehumidifier made of resin can be placed between the pump and the analyzer. This measure can sometimes reduce the effect of the flow rate pulsation significantly. Second, when sample air is drawn by a pump located downstream of the analyzer, a buffer tank or similar device can be placed between the pump and the analyzer to mitigate flow rate pulsation.

When a diaphragm pump is placed upstream of the analyzer, dust which originates from the diaphragm inside the pump frequently contaminates the interior of the cell of the analyzer. To avoid such contamination, make sure to install a filter on the exhaust side of the pump.

Maintenance method

As diaphragms wear out, they need to be replaced regularly. When a diaphragm is damaged due to cracks or other causes, the flow rate may decline and air leakage may occur. Diaphragms and valves are sold separately as replacement parts, so it is advisable to purchase a few in advance as spares. When the flow rate declines, it is suggested to replace the diaphragm of the pump as a first measure. It is also recommended to replace the valves at the air inlet and outlet at the same time. If the flow rate does not recover despite the replacement of the diaphragm, the pump itself might have come to the end of its operational lifetime, and the whole pump should be replaced.

Tips!

The wear-and-tear of a diaphragm changes according to the use conditions. Even when the flow rate of a pump does not decline, it is advisable to replace the diaphragm regularly (e.g., schedule a replacement once a year). Although the operational lifetime of the pump is also expected to change according to the use condition, the investigator should refer to the operational lifetime of the pump suggested by the manufacturer. (Note: In most cases, it is likely that pumps can be used for a longer time period than the operational lifetime suggested by the manufacturer.)

There are numerous diaphragm pump manufacturers. The author has used pumps manufactured by Enomoto Micro Pump and ULVAC KIKO, Inc., Japan. These manufacturers distribute pumps as well as only the consumable parts. (The consumable parts of pumps manufactured by KNF Neuberger GmbH, Germany and Gast Manufacturing, Inc., US can also be purchased from the manufacturers.)

Tips 2.3-5

Tips!

Due to the degradation of the diaphragm or the pump structure itself, air leakage sometimes occurs inside a pump. As a result, air from the surroundings of the installation site of the pump sometimes gets drawn into the pump. In order to check for air leakage, the following simple method can be used. Seal the inlet of the pump with a cap such as that manufactured by Swagelok Company, US and attach a flow meter to the outlet of the pump. Operate the pump and check the flow meter reading. If the air leakage is large, the surrounding air is drawn into the pump through the leak and the flow meter reading becomes different from zero and indicates the degree of air leakage. Note that the proposed method is unable to detect small air leakages. Finally, when the pump operation required for the above-mentioned method is performed over a long time, the burden on the pump becomes large. Thus, caution is necessary while examining the pump for air leakage.

Tips 2.3-6

(4) Tubing

When a closed-path gas analyzer is used for eddy covariance measurements, air is sampled through tubing. For this purpose, a variety of tubing has been used, and the tubing length has varied between a few meters to 50 m or more according to the field site.

Typical tubing that is used with closed-path analyzers includes PTFE tubing, polyethylene tubing, stainless steel tubing, polyethylene-coated aluminum tubing (e.g., Decabon tubes, Hagitec inc., Japan), and plastic tubing (e.g., Bev-A-Line tubing, Thermoplastic Processes, Inc., US). For measurements of the atmospheric background CO_2, stainless steel tubing is often adopted as little CO_2 is adsorbed and penetrates into the tubing. However, stainless steel tubing is hard to work with when it is deployed on a tower, thus, stainless steel tubing is rarely used for tower-based CO_2 flux observations. Instead, pipework that is based on PTFE tubing is frequently used for tower-based CO_2 flux observations with closed-path analyzers. As for the inner diameter of the tubing, 4 ~ 8 mm is typically used. Properties of PTFE include excellent chemical resistance, heat resistance, and weather resistance. PTFE is also nonhygroscopic and non water-absorbing. For tower flux observations, it is necessary to place tubing in an outdoor environment in which the tubing is likely to be exposed for a long time to ultraviolet radiation and reactive gases such as atmospheric ozone. Therefore, the heat-resistant, weather-resistant, and nonhygroscopic properties of PTFE are highly beneficial for use in tubing for tower observations. Polyethylene tubing is more elastic, easier to handle, and less expensive than PTFE tubing. However, the weather-resistance of polyethylene tubing is inferior to that of PTFE tubing, and polyethylene tubing needs to be checked and replaced regularly.

Short tubing length is often used for observations at sites with short plant canopies such as farmland or grassland. In contrast, long tubing length is often used for observations at sites with tall plant canopies such as forests. Even for measurements above forests, if the measurement system as in Fig. 2.3-1 can be established in the middle of the observation tower, the tubing length can be made short. When an observation hut is situated at the bottom of a tower, the measurement system is sometimes installed inside the hut instead of in the middle of the tower. Although the maintenance of the measurement system in this case becomes easier, the tubing length becomes longer than it would be in the case with the measurement system installed in the middle of the tower.

Tips!

Make sure to use appropriate tubing connectors for connecting tubing sections. For connection points that need to be disconnected after the initial deployment, the use of one-touch connectors (e.g., products of NIHON PISCO CO., LTD., Japan) is convenient. For connection points that will not need to be disconnected after the initial deployment, a permanent connection should be selected with the use of fittings such as Swagelok tubing fittings. When tubing connectors are fixed with screws (e.g., connections between a connector and a pump or between a connector and a valve), it is recommended that thread seal tape be wrapped around the junctions to avoid leakage.

Tips 2.3-7

Tips!

Some tubing, e.g., PTFE tubing, is sometimes difficult to purchase in large lengths. For example, when the author intended to purchase PTFE tubing with a 6 mm inner diameter and an 8 mm outer diameter (for drawing sample air), 100m rolls were the next longest size available after 50 m rolls. As only 53 m of tubing was needed, 47 m had to be left unused. (Of course, the left-over tubing should not be discarded, but instead should be kept for other uses.) PFA tubing, a type of fluorine resin (fluoroplastic) tubing, is characterized by low permeability to the surrounding gases and is transparent in color, which allows the investigator to check for accumulations of dirt and dust inside the tubing.

Tips 2.3-8

Tips!

In relation to Tips 2.3-7, the standards of screws that are widely used for screw-in tube connectors include: 1) PT screws that conform to International Organization for Standardization, ISO standards (and also to Japan Industrial Standards, JIS); and 2) NPT screws that conform to American National Standards Institute, ANSI standards. While both of these kinds of screws are taper screws, the helix and pitch angles differ between the two kinds of screws, and mixed usage of these screws causes leakage. Therefore, make sure to check the standard of the screws to be used and also to match up the standards of the male and female parts. Furthermore, because tubing is sized in inches and millimeters, the investigator needs to be cautious when selecting tubing for use.

Tips 2.3-9

(5) Mass flow controller

A mass flow controller is a device to control the flow of sampled air for attaining a constant flow rate. It is highly recommended to install this device as a part of the measurement system. The detailed principles of the operation of a mass flow controller will not be discussed here. Temporary flow rate control can be performed manually with a flow meter with a needle valve (float type). However, a change in the flow rate with time cannot be avoided. In contrast, a mass flow controller is able to adjust the flow rate exactly to the pre-set flow rate. A mass flow controller also suppresses pump pulsation (pressure variation), thus serving a dual purpose.

Tips!

When a mass flow controller is used, the work required by the investigator to control the flow rate is substantially reduced. Some of the commercially available mass flow controllers are equipped with the capability of outputting the flow rate in analogue or digital format, which allows the investigator to monitor the flow rate. The author has used mass flow controllers manufactured by Horiba, Ltd., Japan and Yamatake Corporation, Japan. The author recalls that it was a thrilling experience to use a mass flow controller for the first time: the flow rate variation due to pump pulsation disappeared and the float of the flow meter stopped moving!

Tips 2.3-10

Tips!

A minimum pressure difference is required between the inlet and the outlet of a mass flow controller. The value of the required minimum pressure difference depends on the model. In order to fulfill the requirement of the minimum pressure difference, appropriate decisions need to be made about the pump settings and the opening and closing of a relief valve. (Note: If the pressure difference is too large, the burden on the pump becomes large and water condenses inside the piping. Thus, it is suggested that the pressure be set to a value slightly larger than the value of the required minimum pressure difference.)

Tips 2.3-11

(6) Dehumidifier

The process of moisture removal from the sample air for gas analyzer needs to be carried out without disrupting the gas composition or the air flow. For this process, the use of a dehumidifier that employs a semipermeable membrane, such as Perma Pure dryer (Perma Pure LLC, US) equipped with Nafion tube (DuPont, US) is recommended. This dehumidifier consists of a dual-tube structure; the inner tube is made of a membrane material that is selectively permeable to water vapor. Furthermore, semipermeable membrane dryers are classified into two types. The first type is made of a single semipermeable- membrane tube, and the second type is made of a bundle of semipermeable-membrane tubes. The former is well-suited for drying small volumes of gas while the latter is well-suited for drying large volumes of gas. Use the former type, i.e., single tube type, such as the MD-Series manufactured by Perma Pure, for an observational system in which a closed-path analyzer is used for the eddy covariance method. In single tube-type dryers, sampled air (air containing water vapor) flows through the inner tube, and dry air (purge gas) flows through the outer tube. According to the difference in water vapor pressure across the semipermeable membrane, moisture in the sampled air passes through the membrane and is extracted from the sampled air stream. When sampled air flows inside the tubing of the dryer, moisture removal takes place at high speed; thus, the air flow is not disrupted. Note that the moisture removal efficiency decreases when the flow rate is high. Furthermore, the recommended flow rate of the purge gas is twice to five times the flow rate of the sampled air. For purge gas, gas in a cylinder or air that has been filtered through a desiccant (e.g., silica gel) can be utilized. Finally, the use of a heatless dryer such as the HD-0.5 manufactured by CKD Corporation enables the production of dry air without maintenance for several years.

The closed-path gas analyzers of the present day are able to simultaneously measure CO_2 and H_2O. Therefore, when these analyzers are used, moisture removal from the sampled air does not need to be performed in some cases. However, when moisture flux can be measured with the use of a separate instrument, it is recommended that a closed-path gas analyzer is used for only CO_2 measurements to eliminate the influence of water vapor concentration fluctuations on the CO_2 concentration fluctuations. In this case, remove moisture from the sampled air with a semipermeable-membrane dryer.

Tips!

Even when a dehumidifier that uses semipermeable-membrane tubing is employed, all of the moisture in the sampled air cannot be removed completely. In order to enhance the efficiency of moisture removal, the flow rates of the sampled air and purge gas may be adjusted or multiple dehumidifiers can be connected to the air sampling system. Although the adoption of either method does not result in zero water vapor concentration, these methods can reduce the water vapor concentration in the sampled air and eliminate almost all of the fluctuations of the water vapor concentration. (That is, the influence of water vapor concentration fluctuations on CO_2 concentration fluctuations can be eliminated.)

Tips 2.3-12

(7) System control methodology

Changing the flow path with solenoid valves to introduce calibration gas is the minimum system control required for a closed-path measurement system for the eddy covariance method. In the course of switching to the calibration gas, the pump may need to be powered off depending on whether the sub-sampling method is used. When the sub-sampling method is adopted, the exhaust vent is available for sampled air upon injection of calibration gas. Thus, the pump does not need to be powered off. On the other hand, when the sub-sampling method is not adopted, the pump needs to be powered off upon the solenoid valve switchover (or an exhaust vent is required). During the injection of the calibration gas, continue recording the output signals from the CO_2 analyzer with a data logger in the same way as during the time of the measurements of the sampled air.

Make sure to set up the measurement system in such a way that the opening and closing of the solenoid valves (or the turning off and on of the pump) takes place at a fixed time. Time control can be achieved using a relay control with a PC. Alternatively, relays containing microcomputers, such as programmable relays (OMRON Corporation, Japan), can now be used for time control. In recent years, these relays have become available at low cost, and programs created by the investigator allow easy time control of the relays without a PC.

Solenoid valve control by a PC or a programmable relay takes place independently from the data logger, thus cannot be synchronized perfectly with the data recording. The issue of synchronization can be resolved with the use of a data logger manufactured by Campbell Scientific, Inc., US, e.g., the CR1000 and CR3000 which allow digital outputs with programmable control. When the control port of one of the above-mentioned data loggers is on, five volts are output. This voltage output can be used to control the relay, which in turn opens and closes the solenoid valves. Therefore, the use of one of these loggers enables synchronized data recording and solenoid valve control without the need for additional equipment. Finally, the above-mentioned control is possible with any data loggers with functions similar to those of the data loggers manufactured by Campbell.

Tips!

The sub-sampling method is used to set the flow rate between the inlet for air sampling and the pump to the maximum value. By including an exhaust outlet after the pump in the sampling system, excess gas can be removed and a large flow rate can be achieved. This method helps suppress the attenuation of CO_2 concentration fluctuations and the time delay caused by the transport of sampled air within the tubing (Suyker and Verma, 1993).

Tips 2.3-13

Tips!

Photo 2.3-2 shows the control board of a CR1000 and a solenoid valve control which is based on a mechanical relay. Fig. 2.3-2 is an example program prepared with the CRBasic software. In experiments by the author, solenoid valve control has been successfully achieved. However, this success does not necessarily guarantee the success of all future solenoid valve controls by other investigators, thus the example shown in the figure should be used only as a reference. The program example is for switching on control port 1, i.e., port C1, (turning on the solenoid valve) for 10 minutes between 11:50 and 12:00 and between 23:50 and 24:00. Incidentally, in some cases, the use of Photo MOS relays which have recently become available allows direct control of the relay with a control port.

Tips 2.3-14

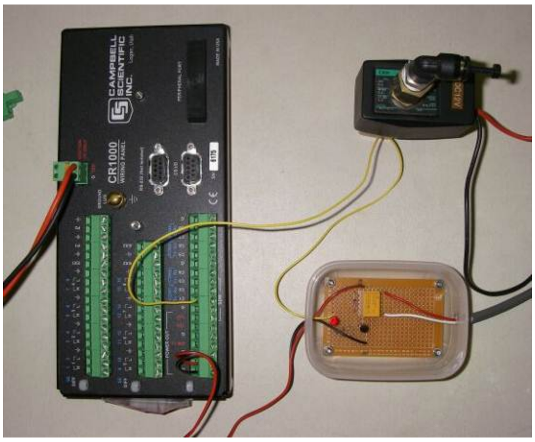

Photo 2.3-2 CR1000 control board and an example of a circuit which controls a solenoid valve with the use of a mechanical relay.

```
'CR-Basic for CR1000
'Main Program
…
BeginProg
…
If IfTime (710,1440,Min) Then PortSet (1,1 )
If IfTime (720,1440,Min) Then PortSet (1,0 )
If IfTime (1430,1440,Min) Then PortSet (1,1 )
If IfTime (1440,1440,Min) Then PortSet (1,0 )
…
EndProg
```

Fig. 2.3-2 An example of a program written with the CRBasic software.

(8) Calibration

A CO_2 analyzer is calibrated by drawing CO_2 gas (standard gas) of different known concentrations into the sample cell. In the calibration procedure, gases of two different concentrations are usually used: a gas with no CO_2 (zero gas) and a gas with a CO_2 concentration slightly higher than that of the air to be measured (span gas). These two gases are used to calibrate the zero point (offset) and span. The value of the zero offset can be detected from the data obtained from the time of the zero gas supply. As for the span drift, it can be calculated from the difference between the output value from the time of the zero gas supply and that from the time of the span gas supply. The zero point offset and span drift can be checked at the time of flux calculations after the data collection. For a more refined calibration of the analyzer, span gases of two different concentrations can be used. In this case, use 1) a standard gas with a CO_2 concentration that is slightly lower than that at the observational site of interest and 2) a standard gas with a CO_2 concentration that is slightly higher than that at the observational site of interest. The calibration method is the same as that in which a zero gas is used. However, with the use of two span gases, the range of CO_2 concentrations to be calibrated can be set according to the CO_2 concentration to be observed, and a more accurate calibration is possible than in the case in which a zero gas and a span gas are used for calibration.

Tips!

Even if a CO_2 analyzer is calibrated frequently, the calibrations are meaningless if a standard gas with low accuracy is used. Thus, it is desirable to use standard gas, the accuracy of which is higher than that of the CO_2 analyzer. In addition, stability of the standard gas over time is also important. Generally, the concentration of the gas in the cylinder increases with a decrease in the residual pressure, thus the gas cylinder needs to be replaced before the residual pressure becomes too low (if possible, before the residual pressure becomes less than 3 MPa.)

Air (air balance) is recommended as the balance gas for the CO_2 gas. (Here, balance gas means the same as base gas or carrier gas.) Although nitrogen is also used as the balance gas for the CO_2 gas, standard gas with air balance is recommended for measuring CO_2 concentration in the air. For details, refer to Pearman (1977), Pearman and Garratt (1975), Griffith (1982), Griffith *et al.* (1982), Nakazawa (1982), and Murayama (2001).

Tips 2.3-15

Tips!

When H_2O concentration is measured simultaneously with CO_2 concentration, the analyzer needs to be calibrated for its H_2O concentration output. There is little water vapor in the standard gas or pure air that is used for CO_2 calibration, thus either gas can be used as the zero gas for H_2O calibration. As for the span adjustment, a dew-point generator (e.g., LI-610, LI-COR) can be used. A dew-point generator produces air with a desired dew-point. The use of an LI-610 allows on-site calibration. (However, make sure to set the dew-point temperature lower than the air temperature of the site.)

Tips 2.3-16

(9) Data output from the analyzer

The value of the concentration measured by the analyzer is output as a digital or analog signal. The LI-6262 is capable of RS-232C output (digital) or voltage output (analog). There are two options for the analog output: raw voltage output and DAC output. The raw voltage output is the output in which no corrections or calculations have been applied, thus, calibration coefficients are required to convert the raw voltage output to concentration values. On the other hand, DAC output is the output in which the value of the concentration has been converted to voltage signals ranging from 0 to 5 V. The LI-6262 is equipped with a data smoothing function, which enables smoothing of the output signal. However, because this function is not necessary for eddy covariance measurements, the smoothing function needs to be turned off by setting the relevant value to 0 seconds.

Similarly, the LI-7000 is also capable of outputting digital signals using an RS-232C connection (the latest versions of the LI-7000 also allow a USB connection) and outputting analog voltage signals (only in DAC output). Analog (DAC) output can be allocated to DAC1 to DAC4 (equivalent of Channel 1 to Channel 4) by assigning appropriate measurement values to appropriate channels. The investigator can set the range of the measurement values of DAC1 and DAC2 to either 0 ~ 5 V or –5 ~ +5 V as the full scale (e.g., set the range of 0 ~ 5 V for the CO_2 concentration range of 300 ~ 500 ppm). Furthermore, a smaller voltage range such as 0 ~ 2.5 V or +0.625 ~ –0.625 V can be selected as the full scale for DAC3 and DAC4. As with the LI-6262, both the digital and DAC outputs from the LI-7000 can be smoothed using the smoothing (filtering) function; however, this function in principle is not needed for eddy covariance measurements.

(10) Location of pump deployment

In the system illustrated in Fig. 2.3-1, the pump is placed upstream of the analyzer, and the interior of the sample cell is pressurized. (The entire portion of the system after the pump is pressurized.) With this pump arrangement, sampled air must pass through the pump before reaching the analyzer. Therefore, with this arrangement, it is impossible to avoid disturbing the sampled air during its passage through the pump. To avoid this circumstance, the pump can be placed downstream of the analyzer. With this method, the entire system is under negative pressure. Because concentration measurements are made prior to the passage of the sampled air through the pump, there is no influence of the disturbance of the sampled air by the pump on the concentration measurement.

If the tubing for drawing in the sampled air is long (e.g., as in a forest), suction resistance becomes large and the pressure inside the tubing becomes low. (The value of the negative pressure becomes large.) When the negative pressure becomes large, it becomes more likely that the air surrounding the tubing leaks into the tubing through the tubing junctions. Therefore, if the tubing length of the system is long, it is recommended to set the pump upstream of all the branching points.

If the observational site is agricultural land or grassland and a short length of tubing can be used for observation, the pump can be placed downstream of the analyzer. However, make sure to minimize the number of branches and connections due to solenoid valves and tubing connectors.

Tips!

For the measurement of CO_2 concentration, small leakages of sampled air under positive pressure reduce the flow rate of the sampled air by only a small amount, and thus the influence of the leakages on the measurement is not large. In contrast, leakage of sampled air under negative pressure causes the surrounding air to enter the system, which significantly influences the concentration measurement. Since the force exerted by negative pressure due to the suction of the pump is larger than one might imagine, extreme care is necessary for the tubing joints. If the piping for the system becomes complex, it is recommended to apply positive pressure (pressurization) rather than negative pressure to the system for easier maintenance and long-term continuous operation.

In order to check the location of leaks in a pressurized system, the use of liquid leak detectors such as Snoop (Swagelok) is effective. Prior to the system operation, check for leaks with liquid leak detectors by applying positive pressure to the system including the portions to which negative pressure will be applied during the time of measurement.

Tips 2.3-17

(11) Attenuation of fluctuations of CO_2 concentration of the sampled air

When a closed-path gas analyzer is used, fluctuations of CO_2 concentration in the measured air (sampled air) are attenuated. The magnitude of attenuation increases with increasing frequency. This issue is considered the biggest weakness of the eddy covariance method that uses a closed-path gas analyzer. The attenuation of fluctuations of CO_2 concentration is caused by the transport of air in the tubing and/or the response speed of the analyzer. The degree of attenuation of the fluctuations varies among measurement systems, and the investigator needs to be aware of the frequency response characteristics of the particular measurement system from the power spectra and other data obtained from the system. If the contribution of the attenuated fluctuations to the fluxes is significant, corrections need to be made to the CO_2 concentration data (high frequency fluctuation correction). A number of correction methods have been proposed, however, the influence of the choice of the correction method is small for observational sites such as forest sites where the periods of fluctuations that contribute to fluxes are relatively long.

A number of publications are available on high frequency fluctuation correction. Refer to Appendix 2.3-1 for some of these publications.

Tips!

When measurements are made with a closed-path gas analyzer, air temperature fluctuations of the sampled air become attenuated in the course of transportation through the tubing. Therefore, the influence of the correction for air density fluctuations (the WPL correction) becomes small. (The correction amount is small.) If 1) the tubing is long, 2) air temperature fluctuations are negligibly small, and 3) moisture has been removed from the sampled air, then the WPL correction will not be necessary (Suyker and Verma, 1993). Furthermore, if water vapor concentration is simultaneously measured with CO_2 concentration, the mixing ratio of CO_2 in the sampled air can be determined. In this case, the WPL correction also becomes unnecessary (Grelle and Lindroth, 1996).

Tips 2.3-18

Appendix 2.3-1: References on corrections for high frequency signals

Aubinet M. *et al*. (2000) Estimates of the annual net carbon and water exchange of forests: the EUROFLUX methodology. Advances in Ecological Research, 30, 113-175.

Lenshow D. H. and Raupach M R (1991) The attenuation of fluctuations in scalar concentrations through sampling tubes. Journal of Geophysical Research, 96, D8, 15259-15268.

Leuning and Judd (1996) The relative merits of open- and closed-path analyzers for measurement of eddy fluxes, Global Change Biology, 2, 241-253.

Leuning R. and Moncrieff J. (1990) Eddy-covariance CO_2 flux measurements using Open- and Closed-path CO_2 analysers: Corrections for analyser water vapour sensitivity and damping of fluctuation in air sampling tubes. Boundary-Layer Meteorology, 53, 63-76.

Massman W. (1991) The attenuation of concentration fluctuations in turbulent flow through a tube. Journal of Geophysical Research, D8, 15269-15273.

Monrcieff J. B., Massheder J. M., de Bruin H., Elbers J., Friborg T., Heusinkveld B., Kabat P., Scott S., Seogaard H., Verhoef A. (1997) A system to measure surface fluxes of momentum, sensible heat, water vapour and carbon dioxide. Journal of Hydrology, 188-189, 589-611.

Philip J. R. (1963) The damping of a fluctuating concentration by continuous sampling through a tube. Australian Journal of Physics, 16, 454-463.

Suyker A. E. and Verma S. B. (1993) Eddy correlation measurement of CO_2 flux using a closed-path sensor: Theory and field tests against an open-path sensor. Boundary-Layer Meteorology, 64, 391-407.

Yasuda Y. and Watanabe T. (2001) Comparative measurements of CO_2 flux over a forest using closed-path and open-path CO_2 analysers, Boundary-Layer Meteorology, 100, 191-208.

2.4 CO_2 storage change

Net Ecosystem CO_2 Exchange (NEE) is generally expressed as the sum of the CO_2 flux observed over the vegetation surface and the observed CO_2 storage change that takes place over time in the space between the ground surface and the flux measurement height:

$$\mathrm{NEE} \equiv F_{\mathrm{c}} + F_{\mathrm{s}} = \overline{w'\rho_{\mathrm{c}}'} + \int_0^{z_{\mathrm{f}}} \frac{\overline{\partial \rho_{\mathrm{c}}}}{\partial t} dz \qquad (2.4\text{-}1)$$

Where, F_c: CO_2 flux at the measurement height [$\mathrm{mgm^{-2}s^{-1}}$], F_s: CO_2 storage change [$\mathrm{mg\ m^{-2}s^{-1}}$], w: vertical wind velocity [$\mathrm{ms^{-1}}$], ρ_c: CO_2 concentration [$\mathrm{mgm^{-3}}$], t: time [s], z: height [m], z_f: flux measurement height [m], ': fluctuating component and $\overline{\ }$: mean value.

The value of the CO_2 storage change is small over short plant canopies such as crops. However, over tall plant canopies such as forests, the value of the CO_2 storage change becomes sufficiently large with respect to the value of CO_2 flux that the CO_2 storage change cannot be neglected (Baldocchi *et al*., 2001). Particularly for several hours after sunrise, the value of CO_2 storage change sometimes becomes as large as or larger than that of the flux. According to Baldocchi *et al*. (2000), the value of the daily CO_2 storage change (total over 24 hours) becomes close to zero, thus can be neglected for evaluating NEE. However, evaluations of CO_2 storage change are required for evaluations of NEE on the time scale of 30 to 60 minutes.

Tips!

In Equation 2.4-1, the horizontal/vertical advection and horizontal turbulence flux terms are neglected. As a result, NEE is expressed only in terms of the vertical turbulence fluxes and storage change. Due to technical constraints, flux observations at the present time usually neglect the horizontal transport terms by assuming “horizontal homogeneity”. Furthermore, because the vertical advection term is difficult to estimate, it is not included in the evaluation of NEE in most cases. Accordingly, it is important to select a site that matches the assumptions in Equation 2.4-1 as closely as possible.

A study on the vertical advection term has been conducted by Lee (1998). In recent years, attempts have been made to evaluate the horizontal/vertical advection terms on the basis of observations (Aubinet *et al*., 2003; Aubinet *et al*., 2005; Leuning *et al*., 2008).

Tips 2.4-1

Measuring procedures

CO_2 storage change is evaluated from the temporal change of the atmospheric CO_2 concentration in the air below the flux measurement height. Because the vertical distribution of CO_2 concentration in the vegetation layer is not uniform, CO_2 concentration must be measured at multiple heights.

When a single closed-path gas analyzer is used, two measurement techniques can be used for evaluating CO_2 storage change: 1) CO_2 concentration can be measured sequentially at each measurement height. In this technique, air is sampled through inlets at multiple heights by switching flow pathways with the use of pumps and solenoid valves; and 2) CO_2 concentration of a mixture of air sampled from multiple measurement heights is measured. An advantage of the former method is that it provides information on the CO_2 concentration at individual measurement heights. Disadvantages of the former method include a somewhat complex controlling system for switching the flow paths as well as a prolonged time interval between measurements. Although these disadvantages can be eliminated by the use of multiple CO_2 analyzers, frequent calibration is required to correct for errors that arise from variations among instruments.

Determination of measuring points/ the number of measuring points

It is desirable to measure CO_2 concentration at as many heights as possible so that the spatially-averaged value of CO_2 concentration can be evaluated. However, when CO_2 concentration is measured sequentially at each measurement height, the measurement interval (the period between measurements) at a particular measurement height becomes larger with an increasing number of measurement points. These factors need to be taken into account when determining the number of measurement points.

CO_2 concentration varies significantly near the soil surface and near leaves (or forest canopy in the case of a forest). Therefore, the heights and number of measurement locations need to be determined appropriately by taking into account the structure of the plant canopy of interest. The effects of the heights and number of measurement locations on the evaluated values of the CO_2 storage change are discussed in Yang *et al*. (1999) and Yang *et al*. (2007).

Measurement system

Fig. 2.4-1 illustrates an example of a measurement system which measures and records CO_2 concentration by sequentially sampling air at multiple measurement heights with a closed-path gas analyzer. In this example, the number of pumps used in the system is the same as the number of measurement heights.

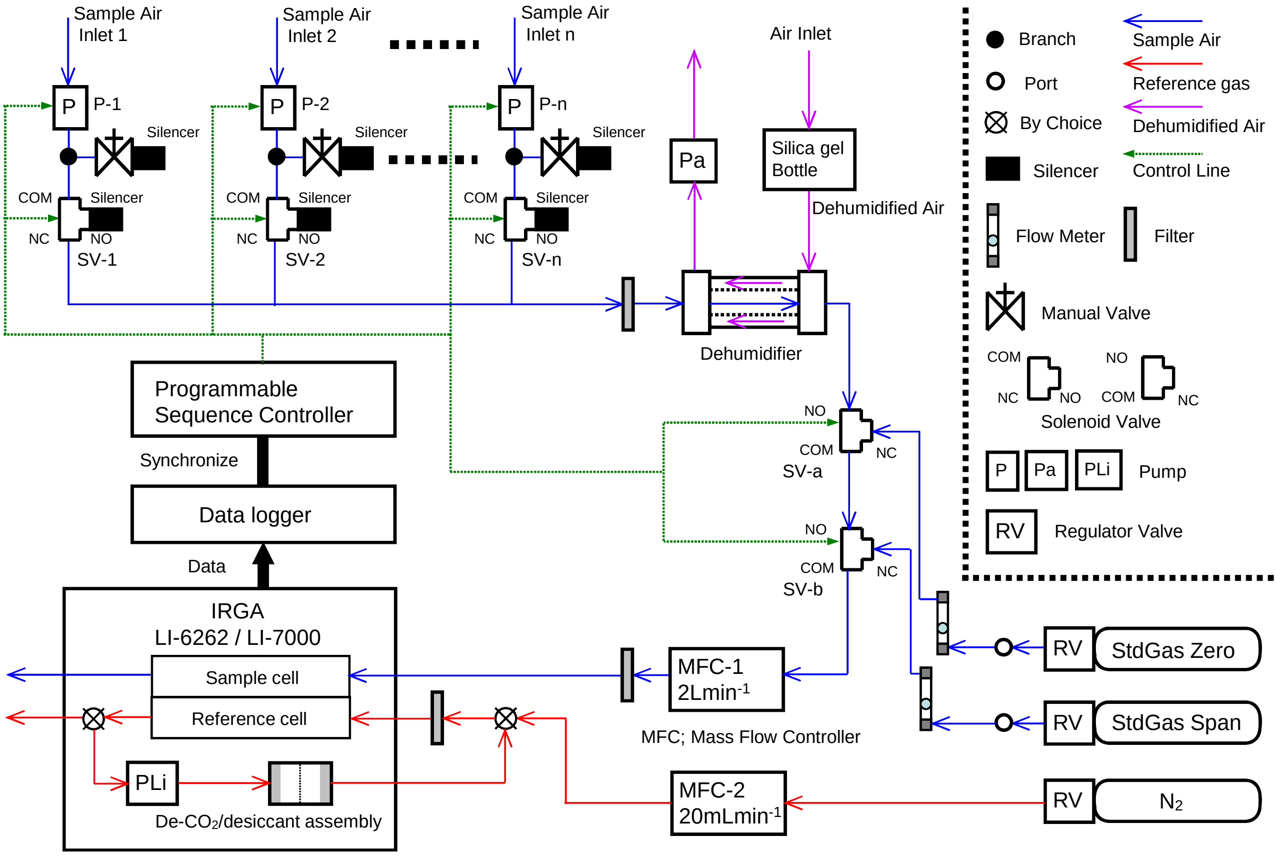

Fig. 2.4-1 A sample system for measuring CO_2 concentration profiles.

The piping in the system can be classified into the following three flow paths:

1. Flow path for supplying sampled air and calibration gas to the sample cell of the CO_2 analyzer (blue path in Fig. 2.4-1)
    - Main flow path: sampled air
    - Merging flow path: calibration gas (zero and span gases)
2. Flow path for supplying reference gas to the reference cell of the CO_2 analyzer (red path in Fig. 2.4-1)
3. Flow path for supplying dry air for dehumidification (purple path in Fig. 2.4-1)

The system itself and cautions regarding its use will be explained by following the flow path for the sampled air and calibration gases in Fig. 2.4-1 (blue path).

Inlets for sampled air

- Fix the end of the tubing so that it points downward to prevent rain droplets from entering (refer to Tips 2.4-2 and photos 2.4-1 ~ 2.4-3).
- Take appropriate measures to avoid taking in rain droplets, dust, and insects.

Suction tubing (piping)

- For outdoor piping, weather-proof tubing such as that made of PTFE (often marketed as “Teflon”) should be used.
- Flexible tubing (e.g., tubing made of polyurethane) is easy to handle in small spaces within the system.

Pumps

- Negative pressure occurs in the flow path upstream of the pump while positive pressure occurs in the flow path downstream of the pump.
- Caution is necessary to prevent leakage along the flow path under negative pressure.
- Caution is necessary to ensure that joints and other parts along the pressurized (positive pressure) flow can withstand the expected maximum pressure.

Manual valves

- A high suction flow rate of air is desirable to shorten the travel time of the air between the air inlet and the sample cell. Excess air should be vented before solenoid valves in order to reduce the pressure to a value less than the maximum allowable pressure of the solenoid valves and the sample cell, reduce the load on the pumps, and prevent dew formation in the mass flow controller.
- The flow rate can be controlled with manual valves.
- When setting up the system, use a flow meter to decide how far to open each valve. During this step, the flow rate of the air after the manual valves should be adjusted to a value close to that set by the mass flow controller.
- Caution is necessary to avoid opening the manual valves too much, as this will cause an insufficient flow rate.
- The valves should be disassembled and cleaned once a year.
- If silencers are added to the exhaust outlets, the silencers should be replaced periodically (approximately once a year) so that clogging of the silencers does not reduce the flow rate of excess air discharge.

Solenoid valves (switching between air samples from various measurement heights) SV-1, SV-2 … SV-n

- Solenoid valves are used for switching between air samples from various measurement heights.
- Prior to opening a solenoid valve, it is recommended that air be drawn in up to the location of the solenoid valve (remove the stagnated air in the tubing between the air inlet and the solenoid valve) in order to shorten the time delay in the measurement due to the distance between the air inlet and the sample cell. For this purpose, create branched tubing between the pump and the solenoid valve for ventilating the excess air. Air is ventilated out of the branched tubing until the solenoid valve is opened.
- The investigator should be aware of the operational lifetime of the solenoid valves.
- Details of solenoid valves can be found in Section 2.3 "Closed-path CO_2 gas analyzers: (2) Solenoid valves".

Air filters

- Air filters should be included in order to avoid problems caused by dust and dirt accumulating in the flow path.
- Moderately priced air filters should be selected for use as the filters need to be replaced frequently.
- Air filters should be replaced once every two to four weeks, depending on the amount of pollution in the air.
- Caution is necessary in selecting both the number of filters to be used and the pore diameters of the filters since these factors can increase the load on the pump.

Dehumidifiers

- When only CO_2 concentration is measured, it is recommended that moisture in the sampled air be removed in order to prevent problems caused by dew formation in the measurement system.
- Purge gas (dry air) that is supplied into the dehumidifiers should be prepared with the use of silica gel or heatless dehumidifiers. (Refer to Section 2.3 "Closed-path CO_2 gas analyzers".)
- The investigator needs to ensure that the dehumidifier is firmly connected to the system tubing. Some dehumidifiers are prone to becoming disconnected from the system tubing.

Solenoid valves (merging of calibration gas) SV-a, SV-b

- The reference gases for the CO_2 analyzer flow through the solenoid valves.
- Attach a pressure regulator to each reference gas cylinder.
  - Follow the operation manual for proper use of the regulator. Because the maximum allowable working pressure varies according to the pressure gauge attached to the regulator, select a pressure gauge with a full scale pressure range of 1.5 to 2 times the pressure to be applied. For example, consider a pressure regulator with an inlet (primary) pressure gauge and an outlet (secondary) pressure gauge. If the values of the maximum pressure at the inlet and the supply pressure at the outlet are assumed to be 15 Mpa and 0.1 MPa, respectively, select a regulator that has pressure gauges with full-scale ranges of approximately 25 MPa and 0.2 MPa.
  - Use a secondary pressure adjustment valve to reduce the pressure sufficiently to avoid applying an excessive load to the system.
  - The pressure range of the secondary pressure adjustment valve should be appropriate for the pressure-tightness of the piping downstream, so that improper opening/closing of this pressure adjustment valve will not impose an excessive load on the piping. Do not select a secondary pressure adjustment valve with high pressure-tightness for versatility.

Mass flow controllers

- The flow rate should be set by taking into account the maximum allowable flow rate for the cells of the CO_2 analyzer.

Filters

- Gelman filters have directionality and must be installed accordingly.

Sample cells of the gas analyzer

- The investigator needs to confirm the maximum allowable inflow rate into and the maximum allowable pressure inside the sample cells by referring to the manual.

Ventilation from the gas analyzer

- When the flow rate is low, installation of an exhaust tube (suggested length: approximately 30 cm on an empirical basis) is required in order to avoid the influence of the outside air.

Tips!

A funnel and a tea strainer (Photo 2.4-1), a film canister (Photo 2.4-2) or a silencer (Photo 2.4-3) can be added to the air inlet. When a film canister is used, it is recommended that a small wad of synthetic cotton be placed inside the canister to prevent insects from entering.

Tips 2.4-2

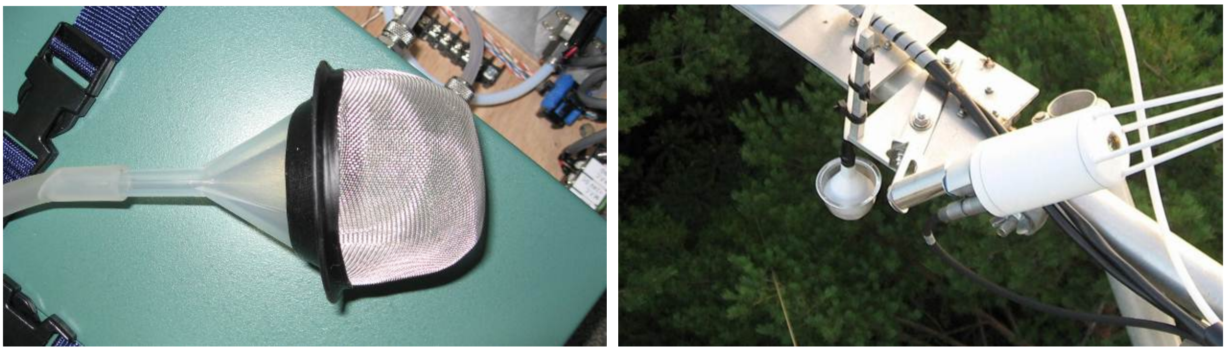

Photo 2.4-1 Air inlet (funnel and tea strainer).

Photo 2.4-2 Air inlet (film canister).

Photo 2.4-3 Air inlet (silencer).

It is suggested that the investigator refer to the above-mentioned cautions for the path marked in red as well as the path marked in blue.

(1) Control system method

The system controls the following two components:

1. Sample air intake at individual measurement heights: control of the pumps and solenoid valves (turning on/off of P-1 ~ P-n and SV-1 ~ SV-n in Fig. 2.4-1)
2. Calibration gas: control of solenoid valves (turning on/off of SV-a and SV-b)

An example of the control for the sample air intake is shown in Fig. 2.4-2. In this example, the pump at the height of the next measurement is “turned on” in advance so that the relevant sample air is drawn to the location immediately ahead of the analyzer. This technique minimizes the delay in the arrival time of the sample air of interest at the time of switching measurement points.

```
hh:mi( P1,SV1, P2,SV2, P3,SV3, P4,SV4, P5,SV5,SVa,SVb)
hh:mi(0,  0,  0,  0,  0,  0,  0,  0,  0,  0,  0,  0)
(0/1:off/on) Pn(n=1～5) pump；SVn (n=1～5,a,b) solenoid valve

・ Standard switching of the measurement points for sample air intake (5 heights)
hh:mi( P1,SV1, P2,SV2, P3,SV3, P4,SV4, P5,SV5,SVa,SVb)
hh:00(  1,  1,  1,  0,  0,  0,  0,  0,  0,  0,  0,  0) Sample 1 taken in
hh:02(  0,  0,  1,  1,  1,  0,  0,  0,  0,  0,  0,  0) Sample 2 taken in
hh:04(  0,  0,  0,  0,  1,  1,  1,  0,  0,  0,  0,  0) Sample 3 taken in
hh:06(  0,  0,  0,  0,  0,  0,  1,  1,  1,  0,  0,  0) Sample 4 taken in
hh:08(  1,  0,  0,  0,  0,  0,  0,  0,  1,  1,  0,  0) Sample 5 taken in
hh:10(  1,  1,  1,  0,  0,  0,  0,  0,  0,  0,  0,  0) Sample 1 taken in
hh:12(  0,  0,  1,  1,  1,  0,  0,  0,  0,  0,  0,  0) Sample 2 taken in
                                        ・
                                        ・
                                        ・

・ Zero gas calibration
hh:mi(  0,  0,  0,  0,  0,  0,  0,  0,  0,  0,  1,  0)

・ Span gas calibration
hh:mi(  0,  0,  0,  0,  0,  0,  0,  0,  0,  0,  0,  1)
```

Fig 2.4-2 An example of a control system for the sampling system shown in Fig. 2.4-1.
(Number of measurement points: 5, frequency of measurement height switchover: every 2 min., time required for a single measurement cycle of the entire profile: 10 min.)

It is recommended that the system for measuring the CO_2 concentration profile be built so that both automatic and manual control of the system are possible. Such a system allows ease of maintenance and response to abnormalities.

When a data logger with an output port (e.g., CR1000, Campbell Scientific, Inc., US) is used, the output values from the CO_2 analyzer can be recorded simultaneously with the switchover of the measurement heights. In this case, mis-synchronization between the time on the data logger and the time of the measurement height switchover can be eliminated. When the system for the measurement height switchover is not linked to the data logger, the voltage of the solenoid valve and the output values from the CO_2 analyzer should both be recorded in order to identify the actual measurement height at which CO_2 concentration was measured.

(2) Examples of other types of systems

The measuring system described above uses the same number of pumps for drawing in sample air as the number of measurement heights. The vertical profile of CO_2 concentration can also be measured by a single pump if it is installed downstream of the location at which flow path switching takes place. However, in this set up, air cannot be drawn in from the next height for measurement in advance. As a result, at the time of the sampling height switchover, the measurement delay will be larger than that in the system described in (1) Control system method. Given this background, Xu *et al*. (1999) created a system that uses two pumps for high-speed sampling of concentration profiles. Furthermore, Ohtani *et al*. (2005) proposed a system that specializes in the measurement of CO_2 storage changes and does not measure concentration profiles. This system takes in air samples simultaneously at six measurement heights within a forest canopy. The average CO_2 concentration of the forest canopy is evaluated by mixing the air samples from the six measurement heights. The proportion of sampled air added to the air mixture from each measurement height depends on the thickness of the air layer that is represented by the measurement height. The CO_2 storage change within the forest canopy is calculated from the temporal change in the evaluated value of the average CO_2 concentration of the forest canopy.

In summary, as these examples show, various types of measuring systems can be designed.

Calculation method

Theoretically, the CO_2 storage change is evaluated from the difference between the instantaneous CO_2 concentration at the beginning of the flux averaging period and that at the end of the flux averaging period. However, this method yields calculation results that differ significantly from the true concentration change of interest (Finnigan, 2006). Although the CO_2 storage change is sometimes evaluated from the difference in the 30-minute average values of CO_2 concentration, this approach underestimates the values that are sought (Finnigan, 2006). Baldocchi *et al*. (2000) calculated the CO_2 storage change from the temporal change of the CO_2 concentration profile (four measurement heights) that was obtained from data collected every 120 seconds.

Because measurements of CO_2 concentration profiles do not provide accurate CO_2 concentration profiles at the beginning and the end of the flux averaging period, Yang *et al*. (2007) calculated the CO_2 storage change by applying a spline interpolation to the measurement values from the measurement heights. In this method, 3-minute average values at the beginning and end of the flux averaging period are used in order to reduce random errors.

Tips!

As shown above, the method for calculating the CO_2 storage change, F_s, varies among research groups, giving the impression that no standardized calculation method has yet been established. However, the following equation is used in every evaluation of the CO_2 storage change:

$$F_s = \int_0^{z_f} \overline{\frac{\partial \rho_c}{\partial t}} dz = \sum_{i=1}^{n} \frac{\Delta \rho_{c_i}}{\Delta t_f} \Delta z_i$$

where Δt_f: flux averaging period, $\Delta \rho_{c_i}$: change in the CO_2 concentration of the air layer i over the flux averaging period, Δz_i: thickness of the air layer i, and n: the number of measurement heights.

Tip 2.4-3

2.5 Relaxed eddy accumulation (REA) method

The eddy covariance method requires a small number of assumptions for flux observations over the ground surface, thus it is considered to be the most direct flux observation method. When the eddy covariance method is used for flux observations of trace gasses such as methane or volatile organic compounds (VOCs), the fluctuating component of the trace gases needs to be measured with a high response time. Such measurements are necessary in order to match the fluctuating vertical wind velocity, *w*, which is measured by an ultrasonic anemometer thermometer (SAT) usually at a sampling rate of approximately 10 Hz. However, when a gas chromatograph (GC) is used for the analysis of trace gases, the analysis requires a few minutes to a few tens of minutes, and the eddy covariance method cannot be used. In this case, the relaxed eddy accumulation (REA) as outlined by Businger and Oncley (1990) can be used instead.

In the REA method, air samples are collected in two isolated reservoirs. An air sample is collected into one of the two reservoirs according to whether it was sampled with an upward or downward vertical wind velocity (positive *w* or negative *w*, respectively). After air samples have been collected over a specified time period, the concentration of the atmospheric trace gas in the air sample in each reservoir is analyzed. Subsequently, the difference in the concentrations of the atmospheric trace gas between the two air samples, $\Delta\rho_g$ [mgm^{-3}], is calculated. The value of the flux, F_c [mgm^{-2}s^{-1}], can be evaluated by multiplying the value of $\Delta\rho_{g,}$ the standard deviation of *w*, σ_w [ms^{-1}], and an empirical coefficient *b*. Thus, the REA method replaces the eddy covariance method when the concentration of a trace gas to be measured is small and the observation calls for the use of a gas analyzer (e.g., GC) that requires some time for concentration analysis.

Measurement principle

The REA method is a variant of the true eddy accumulation method. In flux measurements with the true eddy accumulation method, the flow rate for the atmospheric air sampling is adjusted in proportion to the magnitude of the vertical wind velocity. Over a given length of time, air samples are accumulated in two reservoirs: one for positive (w^+) and one for negative (w^-) wind velocities [ms^{-1}]. This procedure allows evaluation of the time-averaged value of the concentration of the trace gas of interest, ρ_g [mgm^{-3}]. As a true eddy accumulation method, Komori *et al*. (2004) proposed a method that uses syringes connected to a high-speed pulse motor which is synchronized with a pulse generator. In the true eddy accumulation method, the vertical flux of a trace gas, F_g [mgm^{-2}s^{-1}], is expressed as follows:

$$F_g = \overline{w^+\rho_g} + \overline{w^-\rho_g} \qquad (2.5\text{-}1)$$

Because the true eddy accumulation method requires control of the sampling flow rate at a high rate of response, the measuring system becomes complex. On the other hand, the measurement procedure is simplified in the REA method by keeping the sampling flow rate constant. In the REA method, the vertical flux of a trace gas, F_g, is expressed as follows:

$$F_g = b \cdot \sigma_w \cdot \Delta\rho_g \qquad (2.5\text{-}2)$$

where $\Delta\rho_g$ is the difference in the average concentration of an atmospheric trace gas between the two sampling reservoirs and σ_w is the standard deviation of w within a specified time period. The variable b is an empirical coefficient and can be determined from other variables such as the sensible heat flux which can be measured with the eddy covariance method. If the value of b for an atmospheric trace gas flux is assumed to be equal to that of the sensible heat flux, the following relationship holds between the sensible heat flux and the coefficient b:

$$\overline{w'T'} = b\sigma_w(T^+ + T^-) \qquad (2.5\text{-}3)$$

where the left and right sides of the equation represent the sensible heat flux determined from the eddy covariance method and that determined from the REA method, respectively. The variables T^+ and T^- represent the average air temperatures [K] from the times when the values of w are positive and negative, respectively. The above equation can be solved for b as:

$$b = \frac{\overline{w'T'}}{\sigma_w(T^+ - T^-)} \qquad (2.5\text{-}4)$$

The structure of the system used for the REA method

The system for collecting atmospheric trace gases consists mainly of a SAT, solenoid valves, pumps, a mass flow controller, air sampling reservoirs, a programmable recording device such as a CR1000 (Campbell Scientific, Inc., US) and a PC. According to the sign (positive or negative) of the vertical wind velocity, w, the air sample which has been drawn in near the SAT is sorted into the appropriate reservoir. The air sample is sorted with the use of a solenoid valve (Photo 2.5-1) that is operated at high speed. (Refer to Figs. 2.5-1 and 2.5-2; the red and blue lines indicate the flow paths for the positive and negative values of w, respectively.) The flow rate of the sampled air is controlled by a mass flow controller so that the flow rate can be maintained at a constant value. However, it is critical to set the flow rate low (0.2 Lmin^{-1} or less) to ensure that the sampling rate does not exceed the capacity of the sampling tube. At the same time, in order to avoid the influence of wind velocity fluctuations, the air intake rate needs to be maintained at a constant value (4 Lmin^{-1} or larger), and a bypass needs to be included

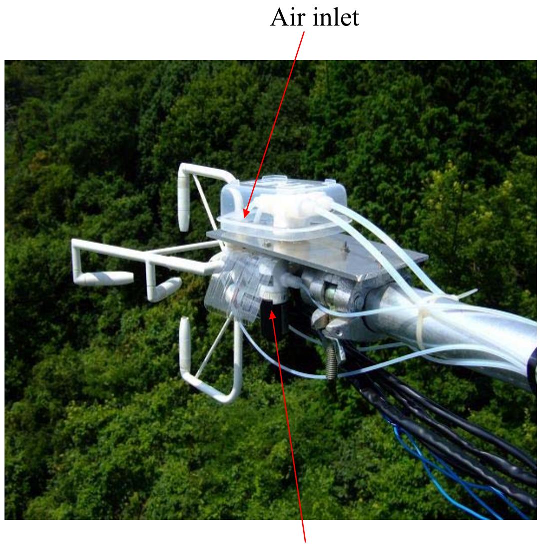

Photo 2.5-1 A SAT and an air inlet used in an REA system. (Yamashiro forest hydrology research site)

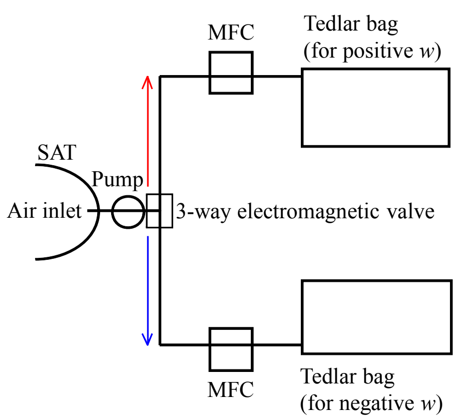

Fig. 2.5-1 Configuration of an REA system for methane.

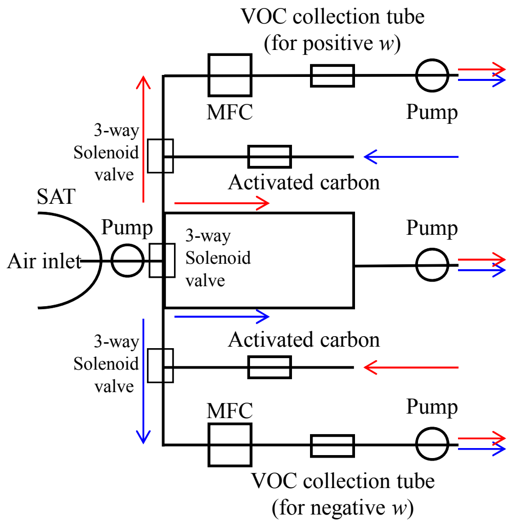

Fig. 2.5-2 Configuration of an REA system for VOCs.

within the measurement system. Additionally, for the purpose of keeping the pressure constant in the system during the solenoid valve switching, the system is equipped with a three-way solenoid valve. When the sampling air inlet is closed, VOC free air that has been filtered through activated-carbon is supplied to the gas sampling tube instead of the sampled air.

A programmable data logger such as the CR1000 is used for 1) controlling the solenoid valves, 2) recording the wind velocities and temperature, and 3) determining the sign (positive or negative) of w according to the moving-average value of w (Photo 2.5-2). In order to exclude the influence of the low-frequency wind-velocity variation, the averaging time for w is selected based on the actual observation conditions, and the averaging time is frequently set to 15 minutes or less. When the averaging time is 15 minutes and the data are recorded at 10 Hz, the sign of w is determined using the moving average of the 9,000 data values up to and including the data value obtained 0.1 seconds before the determination of the sign. In the REA method, a threshold value is sometimes defined for the purpose of eliminating from the analysis the effects of extremely low wind velocities, that is, wind velocities which are lower than the minimum resolution of the data logger or the anemometer. In this case, when the wind velocity is smaller than the threshold value, the trace gas is not stored, but vented out instead (A deadband is set.)

The characteristics of each trace gas are different including its absorptivity, boiling point, and atmospheric lifetime. Therefore, the REA system needs to be configured exclusively for the trace gas to be measured by taking into account its properties and the requirements of the analysis method. For example, large Tedlar bags made of PTFE are often used for storing methane. For storing a VOC such as isoprene or terpene, a reservoir system consisting of multiple air sampling tubes or consisting of canisters is frequently used (Photo 2.5-3). Air sampling tubes are made of stainless steel or glass, are as small as 6 mm in diameter, and are filled with adsorbent. Canisters used for the reservoir system are vacuum vessels made of glass or stainless steel. The reservoir system collects the atmospheric air by automatically switching the flow-path at regular time intervals with the use of programmable relays. The measurement system needs to be designed in such a way that analysis results of high accuracy can be achieved. Specifically, it is necessary to 1) maintain a constant flow rate at a point as close to the air inlet as possible, 2) sort the air samples with a high-speed response time, and 3) store the air samples by minimizing the effects of degradation by ozone as well as adsorption in the flow path. To meet these requirements, it is useful to block ultraviolet radiation, add an ozone scrubber, and use PTFE materials or heating tubes.

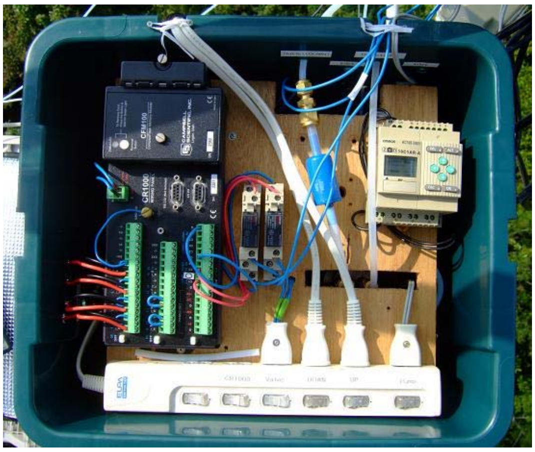

Photo 2.5-2 Control section of a system which is designed for the REA method and uses a CR1000. (Fujiyoshida forest meteorology research site)

Photo 2.5-3 An example of multiple VOC reservoirs (sampling tubes). (Fujiyoshida forest meteorology research site)

Measurement procedure

A typical procedure for trace gas flux measurement is as follows:

1) Observation of w with a SAT and calculation of the time-averaged value of w.
2) Determination of the sign of w, switchover of the solenoid valves, and recording of the determined sign.
3) Automatic exchange of air sampling reservoirs (or on-site automatic analysis of the previously collected air sample during the next sampling period.)
4) If on-site automatic analysis is not performed, the air sample reservoirs need to be brought back to a laboratory. After the analysis equipment has been calibrated with the use of a calibration gas, the air samples are analyzed, and the difference in the concentrations of the trace gas is determined between the times with positive values of w and those with negative values of w.
5) Calculation of the value of b with the use of the sensible heat flux.

Types of analyzers

Although mainly gas chromatographs have been used for the analysis of trace gasses, other types of analyzers have also been used in recent years. Various types of analyzers that are used for trace gas flux observations are described below.

Gas Chromatograph - Flame Ionization Detector

A gas chromatograph-flame ionization detector (GC-FID) reacts only to carbon compounds other than

CO_2 and CO, and is little affected by other constituents of the air. A highly sensitive quantitative analysis of a trace gas of interest can be made by separating the trace gas from the rest of the air sample with the use of an appropriate column. Advantages of the detector include its simple configuration, low price, high stability, and low operating cost. For the analyses of methane and VOCs, an activated-carbon-packed column and a capillary column are used, respectively. The time required for methane analysis is a few minutes. On the other hand, the analysis time required for VOCs is longer than that for methane. In a temperature programmed analysis in which the column temperature is raised for analyzing the high-boiling-point component, cooling time is also required after the analysis. In qualitative analyses, no information other than the retention time of the separated trace gas can be obtained. Therefore, additional information needs to be acquired from a reference substance and a gas chromatograph - mass spectrometer. Because leakage of the hydrogen gas which is required for the analyses may cause an explosion, safety measures should be taken in advance. These measures include the use of a safety device such as an alarm and an automated ventilator for sufficient ventilation.

Gas Chromatograph - Electron Capture Detector

As a measurement principle, a gas chromatograph - electron capture detector (GC-ECD) depends on the change in the base current which takes place when a chemical compound captures free electrons. GC-ECDs are used for detecting nitrous oxide (N_2O), a greenhouse gas that is regulated by the Kyoto Protocol. Because the atmospheric concentration of N_2O is very low (310 ppb), the analysis of N_2O is affected by the peaks of atmospheric N_2 and O_2. Therefore, the heart-cut technique is adopted to extract the constituents that are eluted at and near the peak of N_2O on the chromatograph, and the extracted constituents are analyzed with the detector. In addition, the GC-ECD is highly sensitive in detecting electrophilic substances such as halide and nitro compounds and is also used for analyzing methyl bromide (CH_3Br) which is subject to regulations under the Montreal Protocol. GC-ECDs can be classified into two types: radioactive and non-radioactive GC-ECDs. Use of the former type requires compliance with laws and regulations concerning the conditions for use and storage of radioactive materials.

Gas Chromatograph - Mass Spectrometer

A gas chromatograph - mass spectrometer (GC-MS) is a highly sensitive analyzer and thus is often used for qualitative and quantitative analyses of atmospheric trace gasses. One of the distinguishing characteristics of a mass spectrometer is that it provides mass spectra that include information on the chemical structure of the trace gas of interest. For the analysis of a trace gas with an extremely low concentration, the gas needs to be pre-concentrated in advance. In VOC flux observations using the REA method, air sampling tubes containing adsorbent are frequently brought back to a laboratory for desorption with a thermal desorption unit. A GC-MS analysis is conducted after the air sample is concentrated by cooling the air sample with a cold trap called a cryofocus trap and heat is added to the air sample. Alternatively, air samples can be brought back to a laboratory with the use of canisters, and the samples can be analyzed after moisture is selectively removed with a three-stage trap. This method has enabled the analysis of alcohols which are water-soluble constituents and were previously difficult to analyze. The time required for an analysis with a GC-MS is no different from the time required for analysis with a GC-FID which utilizes capillary columns. However, the maintenance cost of a GC-MS is relatively high compared to that of a GC-FID due to the need to replace turbo-molecular pumps.

Soft Ionization Mass Spectrometer

A proton transfer reaction mass spectrometer (PTR-MS) is a type of soft ionization mass spectrometer and ionizes pure water vapor for the primary ion source. The PTR-MS is able to detect alkane, ethylene, propylene, and acetylene, which are characterized by lower affinity for protons than water. The PTR-MS can detect various other organic gases and hydrogen sulfide. When injecting air samples into the PTR-MS, no pre-processing is required for the air samples such as condensation of the trace gas of interest. Quantitative analyses with a PTR-MS are less prone to measurement errors than those with a GC-MS. A PTR-MS is also capable of continuous and high-accuracy analyses and consecutive quantitative measurements of multiple VOCs at intervals of a few seconds. Recently, based on the high response characteristics of a PTR-MS, the disjunct eddy covariance (DEC) technique has been developed (Rinne *et al*., 2000). This technique conceptually falls between the eddy covariance method which relies on sensors with a fast response time and the REA method. In the DEC technique, atmospheric air sampling periods of less than 1 second are separated in time by intervals of no air sampling. The values of w are recorded, and the air samples are analyzed. This technique aims to include the effect of small-eddy transport by minimizing the sampling time as much as possible. In practical use, virtual disjunct eddy covariance (vDEC) (Karl, 2002) as modified DEC is also commonly used for flux measurement of several compounds.

An ion molecule reaction mass spectrometer (IMR-MS) is another type of soft ionization mass spectrometer. While an IMR-MS is more expensive than a PTR-MS, the former spectrometer is able to analyze any gasses and the sensitivity of the spectrometer is as high as that of a PTR-MS. The IMR-MS uses three gases (Hg, Xe and Kr) as the primary ion sources. Fragmentation (i.e., break-up of molecular ions into smaller pieces due to bond cleavage) occurs more frequently in analyses with an IMR-MS than in those with a PTR-MS, however, an IMR-MS can identify a substance by analyzing the fragments using multiple ion sources. On the other hand, multiple optional ion sources have become available for use in PTR-MSs in recent years, and the differences between an IMR-MS and a PTR-MS have become smaller than earlier.

Tunable Diode Laser Spectrometer

In a tunable diode laser spectrometer (TDLS), two high-reflectance mirrors are set face-to-face in order to obtain an optical path of several kilometers. Within the optical path, laser beams are reflected multiple times, and the attenuation and decay time of the laser intensity are measured. Adjustments for the alignment of the mirrors and the optical source which were required for proper TDLS operations used to be major issues of observations away from laboratories. However, in recent years, these issues have been resolved for some analyzers with the application of optical measures which rely on the use of lenses. Methane analyzers are an example of such analyzers. Regarding the Fast Methane Analyzer DLT-100, (Los Gatos Research, Inc., US) due to its structural feature of having a lens, the volume of the analyzer cell is large (408 ml) thus more suitable for REA method compared to eddy covariance. Therefore, air samples need to be drawn in with a large vacuum pump within a short time interval. As for the methane analyzer G2311-f, (Picarro Inc., US), which is designed for the eddy covariance method, the volume of the cell of the analyzer is small, and it is able to measure H_2O and CO_2 simultaneously using another laser spectroscopy, cavity ring down spectroscopy (CRDS). Laser spectroscopy is expected to be applied in studies of uncovering CO_2 - H_2O exchange process using stable isotopes.

Chemiluminescence Analyzer

For the measurements of isoprene and ethylene, analyzers have been developed with a chemiluminescent method. During the operation of an isoprene analyzer, air is introduced into a reaction cell that is filled with gas containing a high concentration of ozone. Ultraviolet radiation (430 nm) which is emitted from the reaction of isoprene with ozone in the cell is selectively filtered and is measured by an electron multiplier. An ethylene analyzer depends on a property of ethylene that its chemical reaction with certain other substances causes long-lasting chemiluminescence. The chemiluminescent emission from chemical reactions with NO and ozone in a mixing chamber is measured. Finally, chemiluminescent methods are susceptible to the effects of substances that interfere with the chemiluminescent reactions.

Deployment

Selection of deployment location

The air inlet of an REA system should be deployed as close to the SAT as possible, however, in such a way that the air inlet does not affect the vertical wind. Furthermore, in order to minimize the time delay in measurements due to the switching of flow paths, the solenoid valves and their switching system should be placed immediately after the air inlet. Sufficiently high suction force is also necessary so that the air inflow rate at the time of suction is not affected by wind velocity fluctuations. For this purpose, a mass flow controller is used to maintain a constant flow rate. Finally, care is necessary to prevent water from entering the analyzer and to prevent water vapor from condensing inside the analyzer.

Tips!

The Campbell CR1000 is equipped with a terminal with a switch for 12 V DC output (SW12 terminal). Because the SW12 terminal can supply up to 900 mA of electric current at a temperature of 20 °C, this terminal can be used for direct control of solenoid valves. On the other hand, the digital I/O ports, C1 through C8, can output only up to 2.0 mA of electric current at 3.5 V, and thus a relay circuit is necessary for using these ports for control. An example of such a circuit is shown in Chapter 5 of the CR1000 Operator's Manual.

Tip 2.5-1

2.6 Data logger

When flux measurements are made with the eddy covariance method, multiple observational values need to be simultaneously logged at a sampling rate of approximately 10 Hz. When turbulence statistics are sought, the data storage capacity needs to be sufficiently high so that the values of the fluctuating component of *w*, *w*', and of the fluctuating component of a scalar quantity can be stored for several days. The data recorded on the data logger can be transferred to a PC with the use of a communication cable or by swapping the media on which the data are recorded. The use of a versatile digital data format such as the comma separated value (CSV) format allows easy storage and backup of data.

Logger types

Data loggers can be classified roughly into two types: those which first digitalize analog voltage data and record the digitalized data; and those which directly record digital output data. Some data loggers are able to accommodate both logging modes. Storage capacity varies among data loggers. Some of them are equipped with internal memories, and others record data on compact flash storage cards or MO discs (Table 2.6-1). Data logging for turbulence measurements requires a high-speed logging function and a large memory size. For data loggers that are used for other micrometeorological measurements, refer to Section 3.9 “Data logger”. Because turbulence and micrometeorological measurements require different sampling intervals, it is recommended to log the data using two separate data loggers in order to avoid problems. In this case, the clocks of the two data loggers need to be synchronized so that the two data sets are synchronized in time. Incidentally, recent models can be networked for time synchronization.

When values of a physical variable are logged as analog output, it is necessary to be aware of the conversion relationship between the voltage and the value of the physical variable. With this relationship, the ranges of measurements and data logging need to be optimized in advance so that accurate measurements can be made. Because most instruments for measuring turbulence produce output data at 0 ~ 5 V, it is desirable to use a data logger capable of data logging in the range between 0 and 5 V.

Table 2.6-1 Data loggers used for turbulence measurements.

Model (manufacturer)	**A/D resolution**	**Maximum Logging rate**	**Memory medium**
CR3000 (Campbell)	83.33 µV (±5 V)	40 Hz	CF (optional), USB flash drive (optional)
CR1000 (Campbell)	667 µV (±5 V)	10 Hz	CF (optional), USB flash drive (optional)
es8 (TEAC, discontinued model)	16 bit (±5 V)	5 kHz	CF, USB flash drive
NR-1000 (KEYENCE)	16 bit (±5 V)	10 Hz	CF, USB flash drive
MEMORY HiLOGGER LR8430-20 (HIOKI)	500 µV (±10 V)	10 Hz	CF, USB flash drive
ZR-RX20/40A (OMRON)	16 bit (±5 V)	10 Hz	USB flash drive

Tips!

The resolutions of the sensor and the data logger also need to be taken into account in data logging. "Resolution" is the minimum signal variation that can be recognized by the sensor or the minimum signal variation that is allowed in the digital data after an AD conversion by the data logger. As an example, consider a sonic anemometer with a resolution of 0.005 ms^{-1}. If the measurement range is set to ±30 ms^{-1} and the analogue output range of the anemometer is ±1 V, the size of the minimum output signal is approximately 166.7 µV. The minimum output from this case can be recorded only with a data logger with a resolution of at least 166.7 µV.

Tips 2.6-2

The CR1000 and CR3000 data loggers (Campbell Scientific, Inc., US) are highly flexible and are compatible with various measuring instruments. The CR1000 and CR3000 data loggers allow the user to program the voltage measurement range, the logging interval, and the applied voltage. These data loggers are also capable of numerical computations, thus can also record turbulence statistical data.

While many of the sensors which allow digital output use the RS-232C format, some use RS-422 or SDI-12 (Serial Data Interface at 1200 baud rate). Because of the RS-232C standard, the cable length is limited to 10 m or less. If the separation distance between the sensor and the data logger is more than 10m, an optical cable can be used together with a transducer for extending the connection length between the sensor and the data logger. RS-422 signals can be transferred at a maximum speed of 10 Mbps up to a distance of 1.2 km. An RS-422 signal can be converted to an RS-232C signal with a commercially available signal converter. The CR1000 and CR3000 data loggers are equipped with both SDI and RS-232C communication ports, and thus are useful when the sensor and the data logger need to be deployed far apart.

A PC can also be used as a data logger. When a sensor capable of analog output is used with a PC, an analog-to-digital (AD) conversion board is required. Many of the sensors which output digital signals are equipped with an RS-232C interface. However, because RS-232C ports are now obsolete interfaces on PCs (as of 2008), most PCs (as of 2008) are not equipped with these ports. Thus, a USB-RS232C conversion cable or an RS-232C extension board is needed to use a PC as a data logger. Because many types of data loggers support data input to PCs, data can be automatically uploaded to a PC on a regular schedule in order to make up for the insufficient memory size of a data logger.

Most data loggers record data in a binary format in order to maximize memory usage. Furthermore, most of the software which comes with data loggers transfers data to PCs and converts the data on the PCs to the CSV format or other versatile formats. HTTP server and FTP server functions are also available on some data loggers.

Measuring procedures

When an AC power supply is used to operate a data logger, an earth connection is necessary to avoid noise in the data. (The internal switching power supply in a data logger generates noise.) It is also effective to filter out the noise according to the frequency of the power supply. Noise is caused mainly by electromagnetic induction. Effective countermeasures against noise include the following: 1) the signal and power cables should be separated as much as possible; 2) shielded cables should be used; 3) twisted pair cables should be used; 4) the cables should be shortened as much as possible; 5) the cables should not be looped; and 6) the cables should be firmly fixed.

2.7 Detection and reduction of noise

When various sensors are used as in meteorological observations, the measurement values are sometimes affected by noise. Turbulence observations are particularly susceptible to the effects of noise because the sampling rate is relatively high, ranging between a few Hz to a few tens of Hz, and because the measurements require resolutions higher than those sought for general meteorological observations. The noise that affects turbulence observations can be roughly classified into three types:

1) Electrical noise transmitted by signal cables
2) Electromagnetic noise transmitted in the air
3) Noise transmitted by power supply lines (AC power supply lines)

Electrical noise transmitted by signal cables is generated when the insulation resistance or shielding of the sensors is insufficient, or when the signal cables are affected by a power line, a pump, a motor, or electromagnetic waves. Caution is required when wireless equipment such as cell phones and wireless LANs are used for data transmission and monitoring of observation systems as the use of these kinds of equipment causes electromagnetic noise. Noise induced by power supply lines includes instantaneous power failure (indicated by zero voltage for a short time interval such as one cycle), harmonic current (distortion of the original AC waveform due to high-frequency current), voltage drop (voltage drop due to a capacity shortage of the power source or a large distance from the switchboard), and flicker (low-frequency oscillation of the power supply voltage). Particularly when observations are conducted in remote sites or in the areas at which the power supply is unstable, the investigator needs to pay attention to the condition of the supplied power.

Noise detection

The use of commercially available instruments for turbulence observations does not usually pose any serious noise-related problems because those instruments are equipped with sufficient noise-reduction measures. However, at the beginning of an observation or with the replacement of an instrument, the data need to be checked to make sure that they are free of abnormalities.

The most basic data checking procedure is to plot and check the raw measurement values while all the measuring instruments are connected. If the measurement values include spikes, biased values, or ripples related to the power supply frequency, abnormal values will be noticeable even in the data collected at the measuring frequencies that are usually adopted for turbulence observation (approximately 10 Hz). Data can be checked in more detail for noise if the data signals are monitored by an oscilloscope or a spectrum analyzer. When noise is found, the source needs be identified. However, there is no set way to identify the source of noise, and the source can be detected only through trying out various possibilities such as reconnecting signal cables, changing the power supply system, and turning off electric devices such as pumps.

Because the power source can easily cause noise and instrument malfunctions, it is important to check the condition of the AC power source. The power supply voltage can readily be tested with a tester. Various types of power-supply related noise such as those described above can also be checked with an oscilloscope.

Measures to reduce noise

(1) Signal cables

When noise is generated due to insufficient insulation resistance or shielding of a sensor, it is recommended that the sensor be replaced with a reliable one. When a signal cable transmits noise, there are several possible noise suppression measures: keep the cable away from the noise source (e.g., electric devices and wireless LANs); avoid looping the surplus cable; use a twisted pair cable or a shielded cable; keep the signal cable and the power transmission line some distance apart; and cover the signal cable with metal foil or run the cable through a metal pipe.

The sampling frequency used for turbulence observations is approximately 10 Hz, and high-frequency components including the components at the power supply frequency (i.e., 50 Hz or 60 Hz) or higher are spurious. Therefore, it is also effective to apply a low-pass filter (approximately 25 Hz) to the signal cables as in Photo 2.7-1.

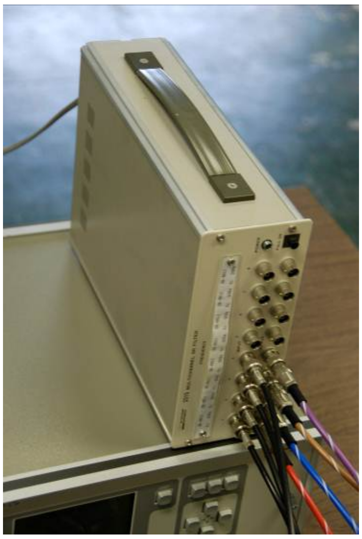

Photo 2.7-1 Low-pass filter for signal cables.

(2) Electromagnetic waves

Cell phones, wireless LANs and CPUs can be sources of noise. Measuring instruments should be kept away from such equipment and should be shielded with metal or other conductive materials.

(3) Power supply

It is effective to apply a noise cut transformer or a lightning shielding transformer to the power supply circuit in order to suppress extrinsic high-frequency noise and surges (Photo 2.7-2). Problems due to instantaneous power failure or voltage fluctuations can be avoided by including an uninterruptible power supply (UPS) in the power supply circuit (Photo 2.7-3). The investigator needs to be also aware that noise may be generated by the switching power supply that is used for supplying DC power to various measuring sensors.

Photo 2.7-2 Noise cut transformer for power supply.

Photo 2.7-3 Uninterruptible power supply unit (UPS).

It is sometimes quite difficult to identify appropriate measures for noise reduction. In designing an observation system which is robust against noise, the following points should be kept in mind:

1) The power supply for the measuring instruments should be separated from that for other electric devices. The use of a noise-cut power transformer is effective to separate the measuring system from other components.
2) When a transformer or a filter is used, the primary and secondary lines should be wired separately and in such a way that they do not get close to each other.
3) The power and signal lines should be kept as far apart as possible. When it is unavoidable to cross the two, they should meet at right angles. When the power and signal lines are installed in an observation hut or on an observation tower, each line should be inserted through separate cable outlets and/or separate vertical pipes so that each line is clearly separated from the other.
4) The signal cable should be made as short as possible to avoid looping.
5) The measuring instruments, data loggers, and signal cables should be kept from devices which produce noise.
6) The earth connection should be carefully arranged. The grounding wires of all measurement instruments should be connected together and to a solid earth terminal.

Tips!

In recent years, an increasing number of turbulence observation instruments provide digital output. Digital output is often less susceptible to noise than analog data output; thus, the use of digital output is recommended if it is compatible with the data logger.

Tips 2.7-1

Related information for chapter 2

Further reading

SDI-12: http://www.sdi-12.org/

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Hamotani K., Uchida Y., Monji N. and Miyata A. (1996) A system of the relaxed eddy accumulation method to evaluate CO_2 flux over plant canopies, Agricultural and Forest Meteorology, 52:135-139.

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Massman W. (1991) The attenuation of concentration fluctuations in turbulent flow through a tube, Journal of Geophysical Research, 96(D8):15269-15273.

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Mizoguchi Y. and Ohtani Y. (2005) Comparison of Response Characteristics of Small CO_2 Sensors and an Improved Method Based on the Sensor Response, Journal of Agricultural Meteorology, 61(4):217-228. [in Japanese with an English abstract]

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Suyker A. E. and Verma S. B. (1993) Eddy correlation measurement of CO_2 flux using a closed-path sensor: Theory and field tests against an open-path sensor, Boundary-Layer Meteorology, 64:391-407.

Wilczak J. M., Oncley S. P. and Stage S.A. (2001) Sonic anemometer tilt correction algorithms, Boundary-Layer Meteorology, 99:127-150.

Yasuda Y. and Watanabe T. (2001) Comparative measurements of CO_2 flux over a forest using closed-path and open-path CO_2 analyzers, Boundary-Layer Meteorology, 100:191-208.

Devices and instruments

2.1

Ultrasonic anemometer thermometers (SATs)

- SONIC CORPORATION, Japan (TR-61A/B/C, TR-90AH, SAT-540/550) http://www.u-sonic.co.jp/english/
- Applied Technologies, Inc., US ("K" Style Probe) http://www.apptech.com/
- Gill Instruments, Ltd., UK (WindMaster, R3, HS) http://www.gill.co.uk/
- R.M. Young Company, US (Model 81000) http://www.youngusa.com/
  - Product list http://www.youngusa.com/products/
  - Price list http://www.youngusa.com/PRICELIST.pdf'
- METEK Meteorologische Messtechnik GmbH, Germany (USA-1) http://www.metek.de/
- Campbell Scientific, Inc. , US (CSAT3) http://www.campbellsci.com/

2.2

Open-path CO_2/H_2O gas analyzers

- LI-COR, Inc., US (LI-7500 family) http://www.licor.com
- ADC BioScientific Ltd., UK (OP-2) http://www.adc.co.uk/
- Campbell Scientific, Inc., US (KH20) http://www.campbellsci.com/

2.3

Closed-path CO_2 gas analyzers

- LI-COR, Inc., US (LI-6262, LI-7000) http://www.licor.com/

2.4

Closed-path CO_2 gas analyzer

- LI-COR, Inc., US (LI-820, LI-840) http://www.licor.com/

Air sampling devices

- Dylec, Inc., Japan http://www.dylec.co.jp/ [in Japanese]
- MEIWAFOSIS CO., LTD, Japan http://www.meiwafosis.com/ [in Japanese]

System building

- CLIMATEC,Inc., Japan http://www.weather.co.jp/ [in Japanese]

Control modules

- Campbell Scientific, Inc., US (SDM-CD16AC) http://www.campbellsci.com/

2.5

Programmable data loggers

- Campbell Scientific, Inc., US http://www.campbellsci.com/index.cfm

Gas chromatographs

- SHIMADZU CORPORATION, Japan http://www.shimadzu.com/
- Agilent Technologies, Inc., US http://www.home.agilent.com/

Soft ionization mass spectrometers

- Ionicon Analytik Gesellschaft m.b.H., Germany http://www.ptrms.com/
- V&F Analyse- und Messtechnik GmbH, Germany http://www.vandf.com/

Tunable diode laser spectrometers

- Los Gatos Research, Inc., US (DLT-100) http://www.lgrinc.com/
- Picarro Inc., US (G2311-f) http://www.picarro.com/
- Campbell Scientific, Inc., US http://www.campbellsci.com/

Chemiluminescent analyzers

- Hills-Scientific, US http://hills-scientific.com/
- Yanaco New Science Inc., Japan http://english.yanaco.co.jp/

2.6

Data loggers

- Campbell Scientific, Inc., US http://www.campbellsci.com/
- TAIYO KEIKI Co., Ltd., Japan (the sole agent of Campbell)
  http://www.taiyokeiki.co.jp/ [in Japanese]
- HIOKI E.E. CORPORATION, Japan (MEMORY HiLOGGER LR8430-20)
  http://www.hioki.com/
- KEYENCE CORPORATION, Japan (NR-1000) http://www.keyence.com/
- TEAC CORPORATION, Japan (es8) http://www.teac.co.jp/indexe.html
- OMRON Corporation, Japan (ZR-RX20/40A) http://www.omron.com/

RS-232-to-RS-422/485 Converters

- Moxa Inc., US (TCC-80) http://www.moxa.com/

Cables for RS-232-to-USB conversion

- I-O DATA DEVICE, INC., Japan (USB-RSAQ5 series)
  http://www.iodata.com/
  http://www.iodata.jp/product/mobile/serial/
  [in Japanese]
- RATOC Systems international, Inc., Japan (REX-USB60F)
  http://www.ratocsystems.com/english/
  http://www.ratocsystems.com/products/rs232c.html
  [in Japanese]

2.7

Oscilloscope

- NF CORPORATION, Japan http://www.nfcorp.co.jp/english/
- IWATSU TEST INSTRUMENTS CORPORATION, Japan
  http://www.iti.iwatsu.co.jp/index_e.html

Digital multimeter

- NF CORPORATION, Japan http://www.nfcorp.co.jp/english/
- ADC CORPORATION, Japan http://www.adcmt.com/index.htm

Low pass filter

- NF CORPORATION, Japan http://www.nfcorp.co.jp/english/

Noise cut transformer

- DENKENSEIKI Research Institute Co., Ltd., Japan http://www.denkenseiki.co.jp/english/

UPS

- DENKENSEIKI Research Institute Co., Ltd., Japan http://www.denkenseiki.co.jp/english/
- OMRON Corporation, Japan http://www.omron.com/ http://www.omron.co.jp/ped-j/dengen/product/ups/ [in Japanese]
- SANWA SUPPLY INC., Japan http://www.sanwa.co.jp/ [in Japanese]
- SANYO DENKI CO., LTD., Japan http://www.sanyodenki.co.jp/en/

Parts and supplies (Some examples)

1. Paper towel, ("Kimwipes" S.Ply 4.4"×8.4" /Bx 280): Kimberly-Clark Corporation, US http://www.kimberly-clark.com/ **[2.2]**
2. Tube connectors: NIHON PISCO CO., LTD, Japan http://www.pisco.co.jp/english/pisco.htm **[2.3]**
3. Tube connectors: Swagelok Company, US http://www.swagelok.com/ **[2.3]**
4. Tubes and PTFE products: CHUKOH CHEMICAL INDUSTRIES, LTD, Japan http://www.chukoh.co.jp/eng/ **[2.3]**
5. Tubes and polyethylene products: HAGITEC CO.,LTD., Japan http://www.hagitec.co.jp/homeeng.htm **[2.3]**
6. Filters: Advantec Toyo Kaisha, Ltd., Japan http://www.advantec.co.jp/english/ **[2.3]**
7. Filters: Millipore Corporation, US http://www.millipore.com/ **[2.3]**
8. Seal tape and PTFE products: NITTO DENKO CORPORATION, Japan http://www.nitto.com/ **[2.3]**
9. Mass flow controllers: Yamatake Corporation, Japan http://www.azbil.com **[2.3]**
10. Mass flow controllers and flowmeters: KOFLOC (KOJIMA INSTRUMENTS INC.), Japan http://www.kofloc.co.jp/kofloc_e/index.html **[2.3]**
11. Solenoid valves: CKD Corporation, Japan http://www.ckd.co.jp/english/ **[2.3]**
12. Solenoid valves: TAKASAGO ELECTRIC, INC., Japan http://www.takasago-elec.com/ **[2.3, 2.4]**
13. Solenoid valves: KOGANEI CORPORATION, Japan http://ww1.koganei.co.jp/en/ **[2.3]**
14. Dehumidifiers: Perma Pure LLC, US http://www.permapure.com/ **[2.3]**
15. Pumps: Enomoto Micro Pump Mfg. Co., Ltd., Japan http://www.emp.co.jp/ [in Japanese] **[2.3, 2.4]**
16. Pumps: KNF Neuberger GmbH, Germany http://www.knf.com/ **[2.3]**
17. Pumps: Gast Manufacturing, Inc., US http://www.gastmfg.com/ **[2.3]**
18. Programmable relay (ZEN): OMRON Corporation, Japan http://www.ia.omron.com/ **[2.3]**
19. Programmable relay (SDM-CD16AC): Campbell Scientific, Inc. US

http://www.campbellsci.com/ **[2.3]**

20. Swagelok, Gaugeable tube fittings and adapter fitting: Swagelok Company, US

http://www.swagelok.com/ **[2.4]**

21. Three-way solenoid valves (FSS-0306YN): Flon Industry, Japan

http://www.flon-ind.com/ [in Japanese] **[2.5]**

3

Micro-meteorological Observation

3.1 Radiation

All objects that are at a temperature higher than 0 K emit energy in the form of electromagnetic waves. The amount of emitted energy is proportional to the fourth power of the absolute temperature of the object (Stefan-Boltzmann Law). The amount of solar radiation emitted by the sun is close to the theoretical value of the radiation from a black body at a temperature of approximately 5,800 K. The spectral peak of the solar radiation is observed around the wavelength of 0.5 μm. Ninety-nine percent of the total solar energy occurs at wavelengths from 0.15 to 3 μm. In contrast, the temperature of the Earth's atmosphere is approximately 300 K. The spectral peak of radiation emitted by the Earth's atmosphere is observed around the wavelength of 10 μm. Most of the radiated energy from the atmosphere occurs at wavelengths from 3 to 100 μm. At the Earth's surface, radiation that originated from both the sun and the Earth's atmosphere is observed. In this section, methods for measuring the radiation originating from these two sources will be discussed.

3.1.1 Solar radiation

Solar radiation is the energy released by the sun. After this radiation enters the atmosphere, it is partially absorbed and scattered by air molecules, water vapor, and dust. Solar radiation that reaches the Earth surface is called shortwave radiation because the wavelengths of the solar radiation range between 0.3 and 3 μm (or between 0.29 and 3 μm).

Solar radiation is classified into direct and diffuse radiation. The direct and diffuse radiation combined together is referred to as global solar radiation.

Types of measuring instruments

The calibration framework for radiation sensors has been established on the basis of the absolute radiometers that are maintained and managed by the World Radiation Center. In addition, the performance standard for radiation sensors is maintained by the International Organization for Standardization (ISO).

The two main types of radiation sensors are thermopile type sensors and photodiode quantum type sensors. The former are commonly used sensors while the latter are simplified sensors. Thermopile sensors can be further classified into heat-sink type and black-and-white type, depending on how the temperature, which is proportional to the solar radiation energy, is evaluated (Ohtani, 1999b). Most of the thermopile sensors distributed currently are of the heat-sink type.

Pyranometers

Various types of pyranometers are commercially available (Table 3.1-1 and Photo 3.1-1). Thermopile pyranometers are equipped with a hemispheric glass dome to cover the heat plate. A frost protection fan can be installed to eliminate the influence of frost and to mitigate the zero-offset problem. The adverse influence of snow accretion can also be mitigated if the snow is not wet.

Pyranometers of various grades are commercially available: ISO secondary standard pyranometers (the highest accuracy available); ISO first class pyranometers, ISO second class pyranometers; and simplified pyranometers.

Table 3.1-1 Characteristics of commonly used pyranometers.

Model	**Manufacturer**	**Sensitivity** $[mV(kWm^{-2})^{-1}]$	**Spectral range** [nm]	**ISO classification**
MS-802	EKO	7	305 ~ 2800	Secondary Standard
PSP	EPPLEY	approx. 9	285 ~ 2800	Secondary Standard
CMP 21	Kipp & Zonen	7 ~ 14	310 ~ 2800	Secondary Standard
MS-402	EKO	7	305 ~ 2800	First Class
SR11	Hukseflux	15	305 ~ 2800	First Class
CMP 6	Kipp & Zonen	5 ~ 16	310 ~ 2800	First Class
MS-601	EKO	7	300 ~ 2800	Second Class
LP02	Hukseflux	15	305 ~ 2800	Second Class
CMP 3	Kipp & Zonen	5 ~ 15	310 ~ 2800	Second Class
ML020VM	EKO	approx. 7	400 ~ 1100	-
SP Lite2	Kipp & Zonen	60 ~ 100	400 ~ 1100	-
PCM-01	PREDE	7 or 10	305 ~ 2800	-

Photo 3.1-1 Examples of commonly used pyranometers.
Left: MS-402, EKO. (Photograph: courtesy of EKO INSTRUMENTS CO., LTD.)
Right: CMP 6, Kipp & Zonen. (Photograph: courtesy of Kipp & Zonen B.V.)

Pyrheliometers

Commercially available pyrheliometers include the MS-56 (EKO INSTRUMENTS CO., LTD., Japan), the CHP 1 (Kipp & Zonen B.V., Netherlands) and NIP (THE EPPLEY LABORATORY, INC., US). In order to eliminate the influence of circumsolar radiation, a cylinder is mounted on the instrument. The cylinder has a small opening and has been treated to control internal reflection. For continuous measurements, an automatic solar tracker (e.g., STR-21, EKO; SOLYS 2, Kipp & Zonen; and SMT-3, EPPLEY) can be employed (Photo 3.1-2).

Photo 3.1-2 Pyrheliometer MS-56, EKO equipped with Solar tracker STR-21, EKO.
(Photograph: courtesy of EKO INSTRUMENTS CO., LTD.)

Diffuse radiometers

In order to measure diffuse solar radiation by eliminating direct sunlight, a shadow band, plate or ball (e.g., PSB-100, PREDE CO., LTD, Japan; CM 121B, Kipp & Zonen; and SBS, EPPLEY) is mounted on a pyranometer. For continuous measurements, a sun tracker (e.g., SOLYS 2, Kipp & Zonen and STR-22, EKO) can be used so that the position of the shadow plate changes automatically according to the position of the sun (Photo 3.1-3).

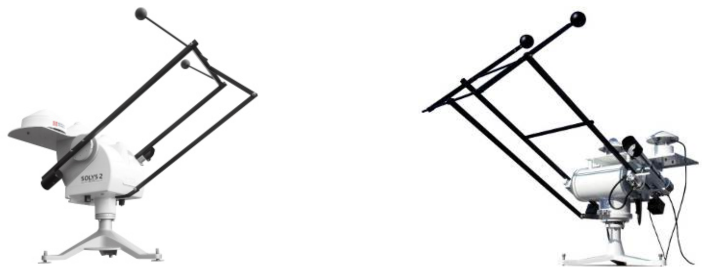


Photo 3.1-3 Measurement of diffuse solar radiation.
Left: SOLYS 2, Kipp & Zonen. (Photograph: courtesy of Kipp & Zonen B.V.)
Right: STR-22, EKO. (Photograph: courtesy of EKO INSTRUMENTS CO., LTD.)

Tips!

The World Radiation Center in Davos, Switzerland, maintains the absolute reference radiometers. In individual districts of the World Meteorological Organization (WMO), a WMO Regional Radiation Center has also been designated. Regional Radiation Centers maintain standard radiometers, intercompare radiometers within a region, and calibrate the standard radiometers against the World Radiometric Reference at the International Pyrheliometer Comparison, a meeting that takes place every five years. The Regional Radiation Centers in the Asia district are located in Japan and India.

Tips 3.1-1

Measuring method

For measuring global solar radiation, a measuring instrument should be deployed horizontally in a location at which the instrument does not get shielded from radiation in any direction. In order to measure the terrestrial energy balance or albedo, two pyranometers with identical characteristics are set up, one facing upward and the other facing downward. Albedometers equipped with a combination of upward and downward facing pyranometers are also commercially available. As measurement errors may occur when the glass dome is not clean, the dome should be cleaned regularly with Kimwipes (Kimberly-Clark Corporation, US) or cotton soaked in alcohol.

In general, the output of a pyranometer is approximately 7 $mV(kWm^{-2})^{-1}$ and small. When data are transmitted over a long distance, the use of thick shielded signal wires is recommended to avoid externally generated noise. For long-term observations, it is desirable to install an arrester on the terminal board to prevent instrument damage due to lightning.

Tips!

A digital multimeter (tester) with a resolution of 0.01 mV, if one is available, is useful for checking the output of a radiometer with small output values.

Tips 3.1-2

Calibration

Because the amount of solar radiation is a key element for studying the terrestrial energy balance, meticulous care is necessary to maintain the sensor accuracy. A radiation sensor can be calibrated by comparing the measurement values from the sensor to those from a highly reliable radiometer around solar noon (Appendix 3.1-1).

Because of the deterioration of the heat-plate coating, the accuracy of radiation sensors used to drift significantly with time, and it was recommended earlier that radiation sensors be inspected every two or three years. The accuracy drift of radiation sensors distributed currently is smaller than that of older sensors.

3.1.2 Longwave radiation

The radiation emitted by the atmosphere or the Earth's surface is called longwave radiation or infrared radiation. The wavelengths of the radiation are 3 ~ 100 μm, longer than those of solar radiation.

Measuring instruments

As with a heat-sink type pyranometer, an infrared radiometer measures the temperature difference between the light-receiving surface and the heat sink with a thermopile. The protective dome of an infrared radiometer is made of silicon rather than glass. The silicon dome (window) reflects solar radiation and allows only longwave radiation to pass through. As the sensing element emits radiative energy according to the

Stefan-Boltzmann law, the infrared radiation that passes through the dome, R_d [Wm^{-2}], can be expressed as follows:

$$R_d = \frac{\Delta E}{k} + \sigma T_b^4 \qquad (3.1\text{-}1)$$

where ΔE: thermopile output voltage [mV], k: thermopile sensitivity [mV(Wm^{-2})$^{-1}$], σ: Stefan-Boltzmann constant (5.67051×10^{-8} Wm^{-2}K^{-4}) and T_b: sensor body temperature [K].

The use of a silicon dome mitigates dome heating caused by the solar radiation absorbed by the dome. However, dome heating cannot be completely eliminated, and accurate measurements sometimes require corrections for the effect of the heated dome. The most commonly used correction formula was proposed by Albrecht *et al*. (1974) and can be expressed as:

$$R_d = \frac{\Delta E}{k} + \sigma T_b^4 + k_d \sigma \left(T_b^4 - T_d^4\right) \qquad (3.1\text{-}2)$$

where k_d: dome coefficient and T_d: dome temperature [K]

Furthermore, Hirose and Shibata (2000) proposed the following equation for evaluating the infrared radiation passing though the dome:

$$R_d = \frac{\Delta E}{k}\left(1 + k_1 \sigma T_b^3\right) + k_2 \sigma T_b^4 + k_3 \sigma \left(T_b^4 - T_d^4\right) \qquad (3.1\text{-}3)$$

where k_1, k_2, k_3: coefficients associated with the temperature of the infrared radiometer.

The values of infrared radiation calculated with Equation 3.1-3 agreed well with the values observed according to the global standard instituted in 2006 (Ohkawara and Takano, 2008). However, because the performance of individual infrared radiometers cannot be easily checked against the infrared radiometer certifying device owned by the Aerological Observatory of Japan, either Equation 3.1-1 or Equation 3.1-2 is frequently employed.

Table 3.1-2 lists the commercially available infrared radiometers that are commonly in use and some of their images are shown in Photo 3.1-4.

Table 3.1-2 Properties of major infrared radiometers.

Model	**Manufacturer**	**Sensitivity** [mV(kWm^{-2})$^{-1}$]	**Spectral range** [nm]	**Window heating offset** [Wm^{-2}]	**Temperature dependency** [%°C^{-1}]	**Measurement of dome temperature**
MS-202	EKO	approx. 4	3,000 ~ 50,000	-	-	yes
PIR	EPPLEY	approx. 4	3,500 ~ 50,000	-	1 (–20 ~ 40°C)	yes
CGR 4	Kipp & Zonen	5 ~ 10	4,500 ~ 42,000	less than 4	1 (–20 ~ 50°C)	no
CGR 3	Kipp & Zonen	5 or 7	4,500 ~ 42,000	less than 15	5 (–10 ~ 40°C)	no

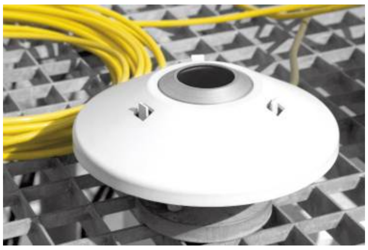
 

Photo 3.1-4 Infrared radiometers.
Left: CGR 4, Kipp & Zonen. (Photograph: courtesy of Kipp & Zonen B.V.)
Right: PIR, EPPLEY.

Measuring method

An infrared radiometer needs to be deployed in a location at which it does not get shielded from radiation in any direction. For downward radiation measurements, the radiometer is deployed horizontally with the sensor side facing upward. Similarly, for upward radiation measurements, the radiometer is deployed horizontally with the sensor side facing downward. When upward radiation is measured, the measurement height needs to be selected by taking the following factors into consideration: if the measurement height is too high, the measurement may include the influence of objects other than the target of observation; if the measurement height is too low, the measurement may be highly affected by the radiometer itself.

Tips!

The thermal converter IRI-01 (PREDE) for the PIR instrument amplifies the thermopile voltage by a factor of 1000 with an amplifier and outputs the amplified voltage. The use of an amplifier often produces noise and sometimes induces errors due to the amplification process. The output from the amplifier needs to be checked with a DC reference voltage generator (e.g., 3K02, NEC Avio Infrared Technologies Co., Ltd., Japan).

Tips 3.1-3

Calibration

Sensors need to be inspected regularly as their sensitivity changes with time. The difference between upward and downward longwave radiation is not as large as the difference between upward and downward solar radiation. Therefore, in order to avoid the influence of difference among radiometers on the radiation measurements, difference among the radiometers need to be examined in advance.

3.1.3 Net radiation

Radiation over the entire wavelength range, combining both solar radiation and longwave radiation, is called all-wave radiation. The difference between the downward and upward all-wave radiation is called net radiation.

Types of measuring instruments

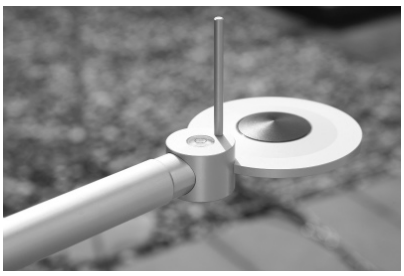
There are two types of net radiometers: net pyrradiometers and four-component radiometers. The former output net radiation directly. The latter physically combines downward/upward shortwave radiometers and downward/upward infrared radiometers.

Net pyrradiometers

A net pyrradiometer includes upward and downward-facing light-receiving surfaces, and the temperature difference between the two light-receiving surfaces is measured with a thermopile (Table 3.1-3, Photo 3.1-5). For protection from the wind, the light-receiving surfaces are covered by domes made of polyethylene that allows radiation of all wavelengths to pass through. Because conventional polyethylene is soft, domes made of this material (e.g., MF-11, EKO) are pressurized with dry air. On the other hand, the Q*7 (Radiation and Energy Balance Systems, Inc., REBS, US) is equipped with rigid polyethylene domes, which require no internal pressurization. Finally, the light-receiving surfaces of the NR Lite2 (Kipp & Zonen) are Teflon-coated instead of being covered by polyethylene domes. This design reduces maintenance work.

Table 3.1-3 Commonly used net pyrradiometers.

Model	**Manufacturer**	**Spectral range** [μm]
MF-11	EKO	0.3 ~ 30
NR Lite2	Kipp & Zonen	0.2 ~ 100
Q*7	REBS	0.25 ~ 60



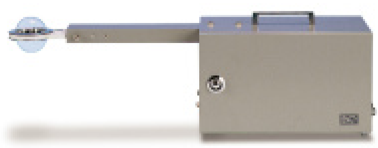


Photo 3.1-5 Net pyrradiometers.

Left: NR Lite2, Kipp & Zonen. (Photograph: courtesy of Kipp & Zonen B.V.)

Right: MF-11, EKO. (Photograph: courtesy of EKO INSTRUMENTS CO., LTD.)

Tips!

Radiometers can be damaged by crows and other birds. Particularly when net pyrradiometers with polyethylene domes are used, protective measures need to be implemented. For example, several wires may be installed around the sensor or fishing lines may be set up at locations on which birds will likely land.

Tips 3.1-4

Four-component radiometers

A four-component radiometer is equipped with relatively small pyranometers and pyrgeometers (Table 3.1-4 and Photo 3.1-6). One pair of sensors faces upward and the other pair of sensors faces downward. Net radiation can easily be evaluated by adding the four radiation components. For this reason, four-component radiometers are currently more often used than the above-mentioned net pyrradiometers.

Table 3.1-4 Commonly used four-component radiometers.

Model	**Manufacturer**	**Spectral range** [μm]		**Temperature sensor of pyrgeometer**
		Pyranometer	**Pyrgeometer**	
MR-60	EKO	0.305 ~ 2.8	5 ~ 50	Body
CNR 1(previous model)	Kipp & Zonen	0.305 ~ 2.8	5 ~ 42	Body
CNR 2	Kipp & Zonen	0.310 ~ 2.8	4.5 ~ 42	None
CNR 4	Kipp & Zonen	0.300 ~ 2.8	4.5 ~ 42	Body
NR01	Hukseflux	0.305 ~ 2.8	4.5 ~ 50	Body

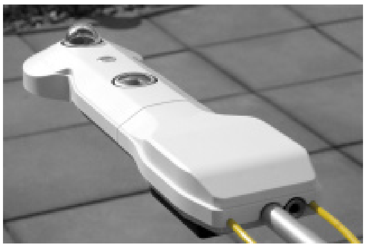



Photo 3.1-6 Four-component radiometers.

Left: CNR 4, Kipp & Zonen. (Photograph: courtesy of Kipp & Zonen B.V.)

Right: MR-60, EKO. (Photograph: courtesy of EKO INSTRUMENTS CO., LTD.)

Measuring method

As with other measurements of radiation components, four-component radiometers are deployed horizontally at a location at which the radiometers are not shielded from radiation in any direction. As measurement errors may occur when the polyethylene domes or sensor protective covers are not clean, the domes and covers should be cleaned regularly with alcohol and Kimwipes. Because polyethylene domes deteriorate quickly, they need to be replaced frequently.

Data processing

A net pyrradiometer evaluates the net radiation from the output voltage and the sensitivity coefficient of the sensor.

When a four-component radiometer is used or when the individual components of downward/upward shortwave radiation and downward/upward longwave radiation are measured, the following equation is used for calculating the net radiation:

$$R_{net} = S\downarrow - S\uparrow + L\downarrow - L\uparrow \tag{3.1-4}$$

Where R_{net}: net radiation [Wm^{-2}], $S\downarrow$: downward shortwave radiation (global solar radiation) [Wm^{-2}], $S\uparrow$: upward shortwave radiation (reflected solar radiation) [Wm^{-2}], $L\downarrow$: downward longwave radiation [Wm^{-2}] and $L\uparrow$: upward longwave radiation [Wm^{-2}].

3.1.4 Photosynthetically active radiation (photosynthetic photon flux density)

Photosynthetically active radiation (PAR) refers to radiation with a wavelength between 400 and 700 nm, which are the wavelengths that chlorophyll can absorb. It is synonymous with photosynthetic photon flux density (PPFD). Its basic unit is $\mu mol m^{-2} s^{-1}$, which can be converted into Wm^{-2} (Appendix 3.1-2).

Types of instruments

Instruments for measuring PAR include spectroradiometers that are capable of measuring irradiance according to wavelength and quantum sensors that selectively sense light between 400 and 700 nm.

Spectroradiometers

One all-weather spectroradiometer is the MS-700, EKO which is of the diffraction-grating type and it measures wavelengths between 350 and 1050 nm. For use of the MS-700, a personal computer (PC) or a logger with a digital I/O port (e.g., CR1000, Campbell Scientific, Inc., US) is necessary to control measurements and save data.

Spectroradiometers are also able to figure out the normalized difference vegetation index (NDVI) which is commonly used in remote-sensing research to indicate the wavelength properties of plant leaves. This particular subject is not addressed in this handbook.

Quantum sensors

As Table 3.1-5 and Photo 3.1-7 show, there are many types of quantum sensors. Unlike pyranometers, for which the World Radiometric Reference (WRR) was established, quantum sensors have no global standards and therefore observation results of sensors differ between manufacturers. Even among sensors of the same type, instrumental error and age-related changes are significant. For this reason, it is necessary to set up a reference instrument and exercise periodic calibration to correct for instrumental error and age-related changes.

Table 3.1-5 quantum sensors.

Model	Manufacturer
LI-190SA	LI-COR
ML-020P	EKO
IKS-27	KOITO
PQS 1	Kipp & Zonen
PAR-01	PREDE
SKP215	Skye

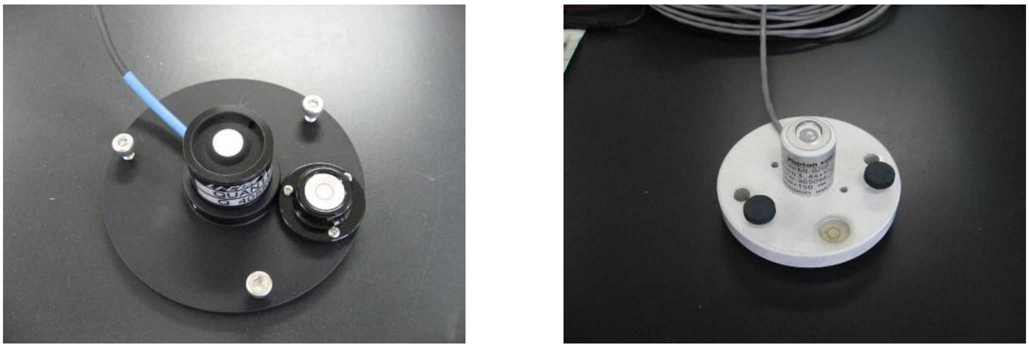


Photo 3.1-7 Quantameters. Left: LI-190, LI-COR. Right: ML020P, EKO.

Measuring method

To measure photosynthetically active radiation incident on a forest canopy, a sensor should be placed horizontally and higher than the canopy.

The amount of radiation absorbed by a forest canopy (absorbed PAR: APAR [μmolm^{-2}s^{-1}]) can be obtained as follows. In remote-sensing research, the balance between downward PAR ($PAR{\downarrow}_{above}$ [μmolm^{-2}s^{-1}]) measured above a forest canopy and reflected PAR ($PAR{\uparrow}_{above}$ [μmolm^{-2}s^{-1}]) is calculated as APAR.

$$APAR = \left|PAR\downarrow\right|_{above} - \left|PAR\uparrow\right|_{above} \qquad (3.1\text{-}5)$$

In research on agriculture/forest meteorology and ecology, more rigorous calculations may be worked out by taking the $PAR{\downarrow}_{below}$ [μmolm^{-2}s^{-1}] and $PAR{\uparrow}_{below}$ [μmolm^{-2}s^{-1}] under a canopy into account.

$$APAR = \left(\left|PAR\downarrow\right|_{above} - \left|PAR\uparrow\right|_{above}\right) - \left(\left|PAR\downarrow\right|_{below} - \left|PAR\uparrow\right|_{below}\right)$$

(3.1-6)

Generally, as the value of $PAR{\uparrow}_{below}$ in a closed forest during a growing season is small, it may be ignored in some cases.

It is desirable to obtain an average value of measurements from more than one point, because values vary widely from place to place when sensors are placed below a forest canopy.

Two of most commonly used instruments are introduced below. One is the LI-190SA (LI-COR, Inc., US), which has an exposed diffuser panel on the surface, and the other is the ML-020P (EKO), which has a glass dome over a diffuse panel to collect radiation.

LI-190SA

1) The sensor outputs the current. In the use of a voltage logger, a precision resistor with a small temperature coefficient (1 kΩ of resistance, 0.1 % accuracy, metal film or wire-wound resistor) is inserted into the logger to convert current to voltage just before the logger (Fig. 3.1-1).
2) If an extension cable is required, a thick coaxial cable (e.g., RG58A/U standard) should be used.
3) Because the BNC connector is not water resistant, waterproofing measures should be taken to protect the connector by treating it with self-bonding tape and then vinyl tape (Photo 3.1-8). It is desirable to encase the device such as to avoid direct contact with water.
4) Regular maintenance is required for the diffuser panel. Alcohol should not be applied.

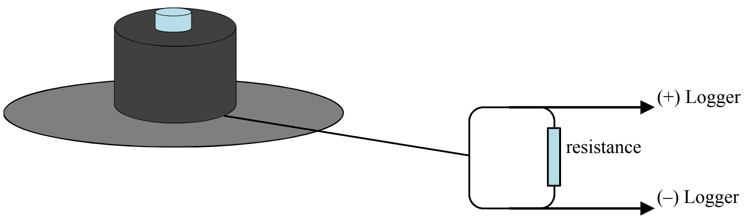


Fig. 3.1-1 LI-190 (current output) and resistance-controlled voltage measurement.

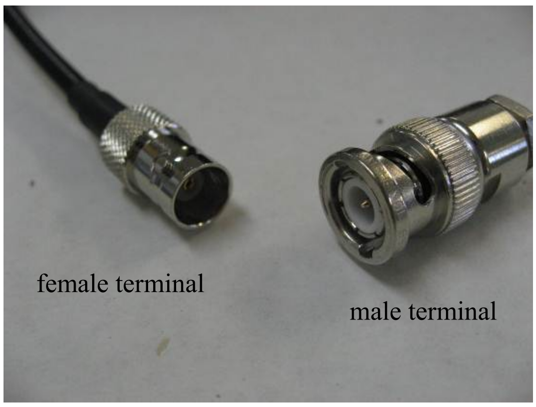


Photo 3.1-8 Cable extended to LI-190.

Left: Wrap self-fusing tape around BNC connecter to waterproof.

Right: Female (cable side) and male (sensor side) connecter.

Tips!

When connecting extension cable to LI-190, attach female terminal of BNC connecter (BNC-R).

Tips 3.1-5

Tips!

The LI-190 has a built-in interference filter to allow light of selected wavelength ranges to enter. It is generally known that inference filters degrade from exposure to water. When the LI-190 is used in a climate of high temperature and high humidity, it needs to be waterproofed by the application of sealant to the sensor bottom, particularly to the cable connection area.

Tips 3.1-6

Tips!

Caution is called for when the temperature of the body case decreases. An ice film may form over the diffuser panel if it is cleansed with Kimwipes (or cotton) that has been soaked in pure water.

Tips 3.1-7

ML-020P

1) The current output from the sensor is converted into the voltage output by the resistor which is inserted in the radiometer. When a long cable is used, a drop in output voltage has to be taken into consideration.
2) The glass dome should be regularly cleansed with Kimwipes or cotton soaked in alcohol.

Tips!

The weight of snow may cause the sensor table to tilt. In a snowy area, an installation table should be reinforced such that it can remain level during the snowfall and snowmelt seasons. It is necessary to confirm that the table is level after the snowmelt season.

Tips 3.1-8

Calibration

Because of large instrument error, the sensor needs to be rechecked before measurement. Because age-related changes are also noticeable, regular instrumental check-ups by the manufacturer or with the reference meter are recommended.

Appendix 3.1-1: Necessary factors to obtain the solar position

The followings are the calculations of factors necessary to obtain the solar position at a given time in a given place.

Equation of time Ω [h]: the difference between mean solar time (hypothetical hour angle on the assumption that the sun moves over the celestial equator at a constant speed) and true solar time (actual hour angle of the sun). Although there are several estimation equations (Matsumoto, 2005), a simple equation is introduced below.

$$\Omega = \frac{1}{60}\left[0.528276\cos(\omega J) - 3.354103\cos(2\omega J) - 0.086077\cos(3\omega J) - 0.137550\cos(4\omega J) - 7.341887\sin(\omega J) - 9.338832\sin(2\omega J) - 0.304815\sin(3\omega J) - 0.170209\sin(4\omega J)\right] \quad \text{(A3.1-1)}$$

where ω = 2π/365 or 2π/366 and J: the number of days elapsed since 0:00, Jan. 1 (real number, e.g., J = 0.5 for 12:00, Jan. 1) which is calculated based on 8-year (1998 ~ 2005) data from the Chronological Scientific Tables.

Hour angle ζ_a [°]: the angular displacement of the Earth's rotation after the sun culmination. The hour angle at the culmination is 0°. The value is negative before the culmination and positive after the culmination, increasing at a rate of 15° an hour.

$$\varsigma_a = 15(t_s - 12 + \Omega) + \gamma - \gamma_0 \quad \text{(A3.1-2)}$$

where t_s: standard time [h], γ: longitude [°] and γ_0: meridian [°].

Declination of the sun δ [°]: the celestial position of the sun. δ = 0° for the equinox, δ = –23.44° for the summer solstice, and δ = 23.44° for the winter solstice. A simple equation is introduced below.

$$\delta = 0.38145 - 22.95333\cos(\omega J) - 0.38122\cos(2\omega J) - 0.153343\cos(3\omega J) - 3.77859\sin(\omega J) - 0.034839\sin(\omega J) - 0.078079\sin(3\omega J) \quad \text{(A3.1-3)}$$

which is calculated based on data (1992 ~ 2005) from the Chronological Scientific Tables.

Culmination time t_a [h]: the time when the sun passes the meridian over the observation point.

$$t_a = 12 - \frac{(\gamma - \gamma_0)}{15} - \Omega \quad \text{(A3.1-4)}$$

Solar zenith angle β [°]**:** the angle between the zenith and the sun.

$$\cos\beta = \sin\varphi\sin\delta + \cos\varphi\cos\delta\cos\varsigma_a \quad \text{(A3.1-5)}$$

where φ: latitude [°].

Solar altitude ζ_s [°]: the angle between the sun and the horizon viewed from the observation point.

$$\sin\varsigma_s = \sin\varphi\sin\delta + \cos\varphi\cos\delta\cos\varsigma_a \quad \text{(A3.1-6)}$$

Appendix 3.1-2: Conversion of measurement units

The relationship between molar photon flux density F_{Q_λ} [molm^{-2}s^{-1}] and radiant flux density F_{E_λ} [Wm^{-2}] of single wavelength can be expressed with Equation A3.1-7.

$$F_{Q_\lambda} = \frac{\lambda \cdot F_{E_\lambda}}{A \cdot h \cdot c_1} \qquad \text{(A3.1-7)}$$

where λ: wavelength [m], A: Avogadro's number (6.023×10^{23} mol^{-1}), h: Planck's constant (6.626×10^{-34} Js) and c_1: velocity of light (2.9979×10^{8} ms^{-1}).

Thus, the relationship between photon flux density F_Q [molm^{-2}s^{-1}] and radiant flux density F_E [Wm^{-2}] integrated in the PAR wavelength range is expressed with Equation A3.1-8.

$$F_Q = 8.36 \times 10^{-9} \int_{400}^{700} \lambda F_{E_\lambda} \, d\lambda \qquad \text{(A3.1-8)}$$

PAR measured by a quantum sensor is limited to the integrated values, and other values for each wavelength are unknown. Accordingly, the conversion into radiant flux density is mostly done with Equation A3.1-9, where a constant α (4.24 ~ 4.57 in the case of natural light) is given on the basis of experimental results of McCree (1972) for the sake of convenience.

$$F_Q = \alpha \times F_E \qquad \text{(A3.1-9)}$$

It should be noted that the constant is not always the same, as the radiant energy at each wavelength changes according to atmospheric and other conditions.

3.2 Wind direction / wind velocity

The direction from which air moves to is called the wind direction, and the distance air moves per unit time is the wind velocity. Wind has to be measured not only as a scalar quantity but also as a vector quantity by taking both the magnitude and direction into account. Surface wind is generally measured as a horizontal flow of atmosphere, as the vertical component is insignificant compared with the horizontal component.

Types of instruments

(1) Wind vanes

The most commonly used instrument for measuring wind direction is the weathercock vane. Two- or three-axis ultrasonic anemometers are now used in some cases.

(2) Anemometers

There are various types of anemometers. These differ by measuring method. The main types are shown below.

Cup anemometer

The cup anemometer, invented by Robinson in 1850, is called the Robinson anemometer. It consists of hemispherical or conical cups and a vertical shaft. Originally it was designed with four cups and a long radius of rotation to gain as much torque as possible. Because of its poor performance, however, the four-cup anemometer was redesigned. For greater efficiency, it was made smaller and more lightweight by reducing the number of cups to three and by shortening the arms. As the cup anemometer has the advantage of being turned regardless of the horizontal direction in which air flows past the cups, it is widely used for determining the average wind velocity. With regard to the wind velocity at which the cups start rotating, the lower it is, the better. Attention should be paid to excessive rotation due to the inertia of the cups in motion.

Windmill anemometers

Unlike the cup anemometer, which has a vertical axis of rotation, this propeller anemometer has a horizontal axis of rotation that makes the propeller anemometer capable of measuring the wind velocity in the direction parallel to the axis of rotation. Most are integrated with a wind vane so that the instrument always faces windward.

Ultrasonic anemometers

Ultrasonic anemometers measure wind velocity based on the time of flight of sonic pulses between pairs of transducers which face each other. Sound waves that are emitted in the same direction as the wind are faster than those emitted against the wind; therefore, there is difference in the travel time of sound waves between receivers. The difference in travel time is proportional to wind velocity, so the wind velocity can be determined by measuring the time difference electrically. Unlike cup anemometers or windmill anemometers, this type does not suffer from the inertia of wind catchers and it is well suited to the observation of wind velocity fluctuations in a short time span. (See Section 2.1 "Ultrasonic anemometer thermometers (SATs)" for details.) Those with a higher resolution of wind velocity (approx. 0.01 ms^{-1}) have come to be available at reasonable prices.

Hot-wire anemometers

In this instrument, a wire is electrically heated while exposed to the ambient atmosphere. Based on the temperature equilibrium between wire heating and wind cooling, the wind velocity is calculated. Although the instrument has high sensitivity at low wind velocities, it cannot be used where rain and snow strike the heating wire and it cannot afford continuous long-time measurement. Therefore, it is mostly used in indoor wind tunnel tests.

Measuring method

Below an altitude of approximately 50 m, which is within the surface boundary layer, the profile of horizontal wind velocity tends to be logarithmic and vertical transport is approximately constant with height. In the surface boundary layer or the canopy layer, where substances and energy are directly exchanged, the wind velocity distribution is complex. For this reason, representative values of wind velocity for a given observation point need to be measured above the canopy layer.

Weather stations carry out regular observations in flat, open spaces that are unobstructed by obstacles such as buildings and trees. The measuring height specified by the World Meteorological Organization is 10m above ground. Japan's Automated Meteorological Data Acquisition System (AMeDAS) conducts observations at 6m above ground.

If research measurement is carried out from a tower, it is desirable to install the instrument as far away from the tower as possible, with the help of devices such as arms in order to avoid having the tower affect the measurements. The tower's effects can be minimized by projecting the instrument in the prevailing wind direction (Photo 3.2-1). When a measurement box is installed in the tower, it should be placed at a different elevation from that of the

Photo 3.2-1 Installed anemometer. (Fujiyoshida forest meteorology research site)

anemometer, to minimize its influence.

By observing the wind velocity in a vertical profile with anemometers placed at four or five elevation points above the forest canopy, the friction speed can be calculated. In this case, as the profile of wind velocity above the canopy tends to be logarithmic, anemometers should be placed more densely as one moves toward the lower heights, to obtain a logarithmic profile of wind velocity with height.

Anemometers of cup type and windmill type contain moving parts. Such anemometers need to be cleaned and lubricated to maintain smooth rotation for long use. Electromechanical components must be replaced and recalibrated regularly. In cold, snowy regions, attention has to be paid to snow and ice accretion.

In installing a wind vane, it should be noted that true north and magnetic north differ.

Tips!

The difference between geographic (true) north and magnetic north is called magnetic declination, *D* [°]. The declination differs from place to place and changes over time. The value as of 0:00 on Jan. 1, 2000, is approximated by the following equation (National Astronomical Observatory of Japan, 2005).

$$D_{2000.0} = 7^{\circ}37.142' + 21.622'\Delta\varphi - 7.672'\Delta\gamma + 0.442'\Delta\varphi^2 - 0.320\Delta\varphi\Delta\gamma + 0.675\Delta\gamma^2$$

$$\Delta\varphi = \varphi - 37^{\circ}\,\mathrm{N}, \quad \Delta\gamma = \gamma - 138^{\circ}\,\mathrm{E}$$

where φ: latitude [°], and γ: longitude [°].

Tips 3.2-1

Record of wind velocity / wind direction data

Wind velocity sensors come in two types in terms of the readout, one with pulse counts and the other with voltage. For wind direction measurement, potentiometers that operate on the basis of resistance are commonly used. Most ultrasonic anemometers are capable of producing voltage output of wind velocity measurements for the x and y axes, as well as digital output of wind direction measurements.

Calibration

Anemometers must be checked frequently. To three-cup anemometers, which contain moving parts, pre- and post-observation tests should be given. Ultrasonic anemometers, which have no moving parts, require little maintenance. However, the voltage signal released from ultrasonic anemometers with analog output is likely to include some residual deviation (about 20 ~ 30 mV at a wind velocity of 0 ms^{-1}). As the amount of residual deviation differs between instruments, zero-point output should be confirmed during installation to give a zero-point adjustment to the output voltage values that are acquired.

Where a wind tunnel is available, tests can be undertaken with real wind velocities that are obtained with the help of a Pitot tube, which measures the wind velocity based on the pressure differential inside and outside the tube (Photo 3.2-2 and Fig. 3.2-1). By the side of the anemometer that is to be calibrated, the Pitot tube is placed such as not to hinder the air flow. While the wind velocity in the tunnel is being varied, comparison and calibration are carried out based on measurements checked at ten or so points. The dynamic pressure (the difference between total pressure and static pressure) measured by the Pitot tube (which is measured beforehand with a differential pressure gauge) and the air density (which changes in response to temperature and therefore should be measured simultaneously with temperature) are input into Bernoulli’s equation in order to calculate the wind velocity.

Photo 3.2-2 Inspection of an ultrasonic anemometer in a wind tunnel.

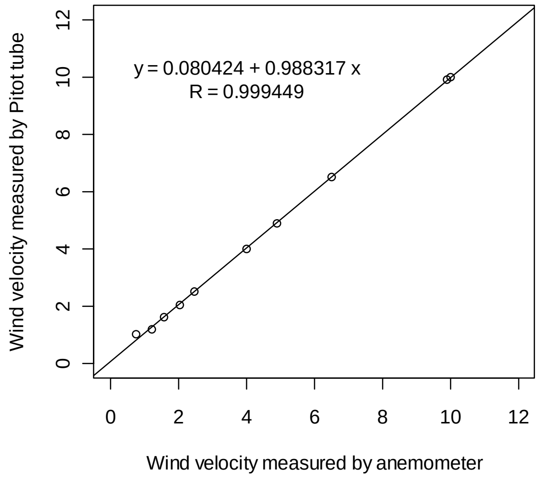


Fig. 3.2-1 Wind velocity (real) calculated through the dynamic pressure of the Pitot tube vs. wind velocity given by the tested anemometer.

Tips!

Equation to obtain the wind velocity (u [ms^{-1}]) using a Pitot tube (Bernoulli’s law):

$$dP = 1/2\ \rho u^2$$

where dP: the difference between total pressure of wind vertical to a Pitot tube hole and static pressure of wind parallel to a Pitot tube hole [Pa] and ρ: air density [kgm^{-3}].

Tips 3.2-2

Tips!

With the aim of establishing national standards of low wind velocity, the National Metrology Institute of Japan has constructed an underground tunnel that is unaffected by surrounding conditions, where the accuracy of anemometers at low wind velocities can be tested by mounting them on a car and running the car at low speeds.

Tips 3.2-3

Data processing

(1) Wind direction

Wind direction is the direction from which wind blows. The direction is indicated by cardinal points (e.g., N, NNE), in azimuth degrees from 0° to 360° clockwise from north, or in 16 or 36 points of the compass for which the circumference is divided into 16 or 36 sections (Fig. 3.2-2).

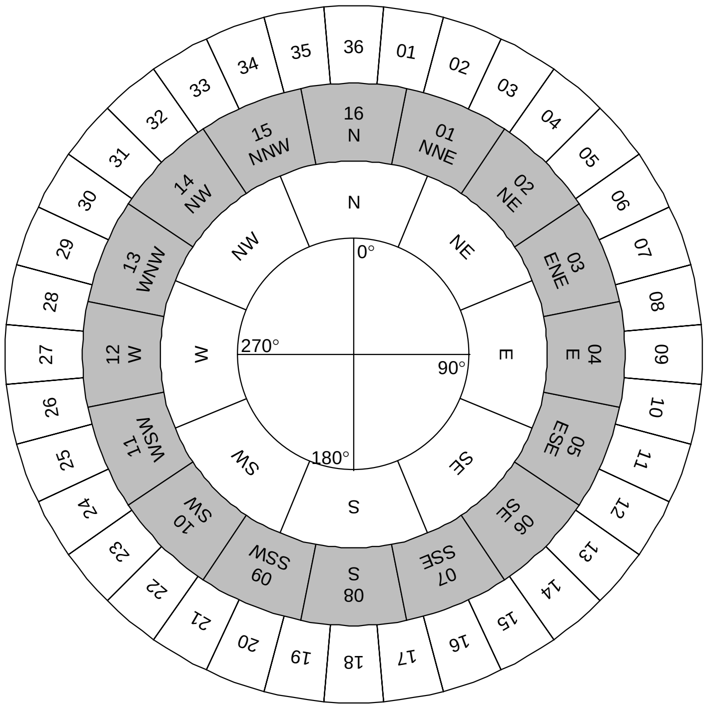


Fig. 3.2-2 Notation of wind direction.

It is desirable to use the average vector as the representative wind direction index. In this case, data of wind direction and wind velocity need to be collected simultaneously. In some cases, the scalar average and the prevailing wind direction within a given time period can be used as the average wind direction. In the case of no wind blowing, the calm value is expressed by "-" or "00".

(2) Wind velocity

Wind velocity can be an instantaneous reading or an average. Unless otherwise specified, the wind velocity is the average of wind velocity measurements for a given period. Regarding instantaneous wind velocity, there is no clear definition of "instantaneous" in terms of seconds, and the observed value differs depending on responsiveness and recording procedure of each anemometer.

3.3 Air temperature

Air temperature is measured with a thermometer. Thermometers are substantially affected by radiation. For accurate measurement they should be installed within a shelter to avoid radiation. Because temperature can fluctuate widely with time and location, a proper thermometer and proper measuring procedures must be chosen to satisfy the observation objectives. In selecting a thermometer, factors including the following should be fully examined: time constant of the temperature sensing unit, durability, required calibration frequency, installation location, number of installation locations, and measured range.

In the International System of Units, [K] is the designated measurement unit of temperature. [°C] is used in usual temperature measurement (Appendix 3.3-1).

Types of instruments

There are various types of thermometers, as Table 3.3-1 indicates. For long-term meteorological observation, platinum resistance thermometers and thermocouple thermometers are most commonly used. These are equipped with a sheath in which a temperature sensing unit is loaded and sealed with insulation. The characteristics of thermometers that are generally used for continuous measurement are discussed in this section.

Table 3.3-1 Thermometers.

Name	Principle	Characteristics
Electrical resistance thermometer	Temperature change in electrical resistance	Easy to handle. The temperature sensing unit is larger than that of a thermocouple.
Thermocouple thermometer	Thermo-electromotive force	The size of temperature sensing unit can be minimized. Each junction needs to be maintained carefully for accurate measurement.
Radiation thermometer	Thermal radiation	Wide-range remote measurement is possible, although it is difficult to maintain the measurement accuracy.
Self-registering metallic thermometer	Metallic expansion	Self-registering, driven by a spring. The measurement accuracy is low.
Fluid-filled thermometer	Fluid expansion	Low-priced instrument. It is high in accuracy, but it needs a reader.
Ultrasonic anemometer thermometer	Ultrasonic Doppler effect	Appropriate for measuring sensible heat flux, the instrument is expensive and requires calibration.

Thermistor thermometers

This thermometer contains a metallic resistor whose resistance decreases as the temperature rises. Because the rate of change in resistance in response to temperature variation is pronounced, this thermometer is well suited to measuring very subtle temperature changes. A thermistor element can be made smaller than a platinum thermo resistor, which is advantageous for the production of size-reduced temperature sensing units. Error and noise caused by resistance of the lead wires can be mitigated by increasing the signal output and electric resistance of the element. Accordingly, remote measurement away from a data logger through extended lead wire becomes possible. The instrument requires regular inspections, as it may be susceptible to self-heating and the age-related changes in the element are relatively great. Because the instrument has strong nonlinearity and its elements are not standardized, it is usually used with a linearizer-integrated special converter. Various handy, low-priced thermometers with a power source and a data logger in, such as the HOBO series produced by Onset Computer Corporation, US (Photo 3.3-1) and the Ondotori series by T&D Corporation, Japan (Photo 3.3-2), are commercially available. Most are used for low-cost automatic continuous measurement and multi-point observation of the thermal environment.

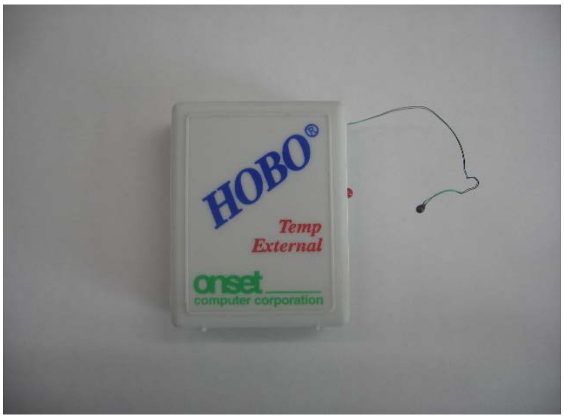


Photo 3.3-1 HOBO by Onset (thermistor thermometer).

Photo 3.3-2 Ondotori by T&D (thermistor thermometer).

Tips!

When no linearizer is available, temperature can be converted after the relationship between temperature and resistance of the element (possibly provided by the thermistor manufacturer) is determined and the voltage supplied from the constant voltage source is measured.

Tips 3.3-1

Platinum resistance thermometer

The instruments are standardized, with Pt100 indicating the resistance of 100 Ω at 0 °C. The three- and four-wire types (Photo 3.3-3) that are often used for meteorological observation have high measurement accuracy, as they are capable of offsetting the resistance value of the lead wire by measuring the output voltage of the bridged circuit. Thus they are well suited for stable, long-term observation. To make wiring resistance uniform, lead wires of the same diameter, material, and length should be used, and corrosion prevention must be given to all the connections. If wire is extended excessively, resistance may increase too much for the data logger to register. Because the heat capacity of a resistance element is greater than that of a thermocouple, the response speed is accordingly slower. The sheathed platinum resistance thermometer is highly resistant to age-related changes, which makes it well suited to long-term observation, but it should be handled carefully as it is susceptible to vibration and shock.

Photo 3.3-3 HMP45D of Vaisala (platinum thermometer, discontinued model, replaced by HMP155).

Tips!

In case of Pt100, between resistances of R_{100} [Ω] at 100 °C and R_0 [Ω] at 0 °C, the ratio R_{100}/R_0 is 1.3850, which conforms to the standard of the International Electrotechnical Commission (IEC). Because the standard (R_{100}/R_0=1.3916) specified in the Japanese Industrial Standards (JIS) before 1989 was different from the IEC's, the standard before 1989 is distinguished as JPt100.

Tips 3.3-2

Thermocouple thermometers

When metal gains a thermal gradient, thermo-electromotive force is generated within the metal as a result of a difference in density of free electrons. If two different kinds of metal wires that generate different electromotive forces at the same temperature are joined at their ends to form a circuit (thermocouple), a current flows in a certain direction as long as a disparity of temperature is maintained between the two points of contact. This is called the Seebeck effect, and it is used by the thermocouple thermometer for temperature measurement (Fig. 3.3-1). The instruments are relatively simple in structure, moderate in price, standardized and therefore compatible with each other. The point that is connected to a data logger is called a reference junction or a cold junction, and its temperature is referred to by the sensor as a base value of temperature. The data logger determines the temperature of the measuring point by sensing the terminal temperature with a thermistor. To avoid the occurrence of temperature difference between terminals, the terminal may be covered to reduce the effects of radiation. For the thermocouple thermometer, the difference in shape and size between metal components of two different materials little affects on the thermo-electromotive force. But the thermocouple thermometer is characteristically susceptible to noises because of high wire resistance to electromotive force. For wire extension, a compensation lead wire appropriate for each type of thermocouple should be used to compensate for the thermo-electromotive force between thermocouple terminal and logger terminal.

For observations from a tower, the copper-constantan thermocouple (T-type), which has high thermo-electromotive force and low resistance, is often used. Because copper readily oxidizes, care should be exercised against corrosion around the junctions. In tower observations, a device with two sheathed thermocouples in a shelter, one as a dry-bulb thermometer and the other as a wet-bulb thermometer, is often used for observing vertical distribution of temperature and humidity.

If high responsiveness is required of temperature measurement, the following method can be used: the ends of copper wire and constantan wire with a diameter of 0.1 mm or so are polished and applied with electric welding or silver soldering, and then the junction is trimmed and covered with thin film insulator. Although the device can be made by hand, a super-fine thermocouple for which the end of the thermocouple wire is welded and processed to 13 μm is supplied by manufacturers such as OMEGA Engineering, INC., US. Although finer thermocouples have higher responsiveness, they are more susceptible to vibration and therefore need to be carefully handled.

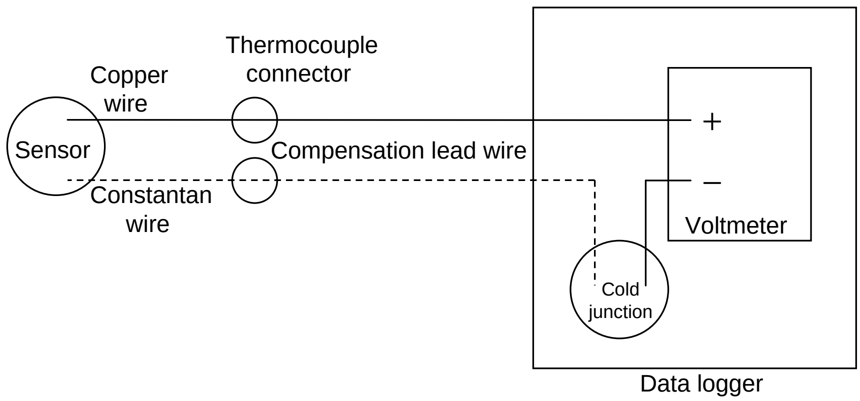


Fig. 3.3-1 Thermocouple circuit.

Photo 3.3-4 Sheathed thermocouple.

Tips!

For silver brazing (soldering), a copper crucible or a copper plate is heated with a burner at a high temperature, and borax and silver solder are put into the crucible to melt. After trimming, the junction sections of the thermocouple are put in the crucible and soldered. The wire diameter is reduced if necessary, and the junction is coated with insulation. For electric welding, a spot welder and optional welding tweezers for thermocouples are appropriate. Although welding kits can be handmade easily (Ohtani, 1999a), due caution has to be taken, as the resistor generates very high heat. The production of a thin thermocouple requires a welder whose voltage and pulse width can be adjusted.

Tips 3.3-3

Measuring method

In measuring temperature, the thermometer should be placed in a shelter to prevent influences of radiation, rainfall and snowfall. In Japan, shelters equipped with a fan that blows at a speed of 3 ms^{-1} or over (Photo 3.3-5) are used in most places. A horizontal shelter needs to be installed, and its installation must be such that solar radiation will not enter. In addition, caution has to be taken so that air can blow in the direction where the fan heat does not affect the observation.

In general meteorological observation, temperature is measured in an open observation field without obstacles. The standard measuring height specified by the Japan Meteorological Agency is 1.5m above ground (snow surface) and that of the World Meteorological Organization (WMO) is between 1.25 and 5 m above ground.

To continuously observe the vertical distribution of temperature, particularly high measurement accuracy is required. In evaluating the static stability of atmosphere, the potential temperature (the temperature which an air parcel would acquire when brought adiabatically to a standard atmospheric pressure) is a key factor of the vertical distribution. However, because the difference in potential temperature is approximately equal to the difference in atmospheric temperature within the surface layer, the atmospheric temperature is often employed. As for the measuring height in a forest, the upper limit is set at a point more than twice the tree height, where the vertical gradient of temperature becomes smaller. Other measuring points may be two elevation points above the vegetation community, one at the tree crown, one under the canopy and one near the ground surface. It is desirable to have as many measuring points as possible.

The radiation thermometer is suitable for measuring a wide range of vegetation surface temperature. For its use, caution has to be exercised regarding the influences observation angle, radiation and shade made by the thermometer itself, quantity and rate of radiation released by substances other than vegetation, and the like.

Photo 3.3-5 Shelter.

Tips!

A shelter fan is prone to breakdown by the entry of foreign matter. Whether the fan is revolving should always be checked, and preparations for replacement in the event of trouble need to be made. Particularly during the summer, when small bugs are occasionally pulled into a shelter in large quantities, a fan and a temperature sensing unit need frequent cleaning. The frequency of cleaning can be reduced by installing a net (that for a drain or a corner strainer in the kitchen sink) over the shelter intake mouth.

Tips 3.3-4

Calibration

Instrument error is simply calibrated with a reference instrument that is placed regularly at the same elevation as the one to be tested. The reference instrument should be inspected by the manufacturer, and age-related changes should also be checked for.

It is desirable to exercise calibration with a commercially available thermometer test bath. A waterproof thermometer is usually tested in a constant-temperature water bath equipped with a water circulator and a temperature control unit.

Tips!

For a test in a constant-temperature water bath, anti-freezing solution is added to keep the water from freezing at low temperature.

Tips 3.3-5

Appendix 3.3-1: Unit conversion

Conversion between Celsius C [°C] and absolute temperature T [K]

$$C = T - 237.15$$

$$T = C + 273.15$$

Conversion between Celsius C [°C] and Fahrenheit X [°F]

$$C = \frac{5}{9}(X - 32)$$

$$X = \frac{9}{5}C + 32$$

3.4 Humidity

Humidity is the amount of water vapor in the air, which is expressed by various indexes depending on the study objectives. These indexes are mutually convertible, although additional data including those on temperature and atmospheric pressure are required. It should be noted that technical terms used for some types of humidity differ slightly between academic disciplines (Appendix 3.4-1).

Types of instruments

The following are the main types of hygrometers that are used in most observations. With the aim of avoiding radiation effects, as in temperature measurement, a shelter is used for all hygrometers except infrared ones. Usually, a thermometer and a hygrometer are placed in a shelter.

Wet and dry bulb thermometers

One of the two juxtaposed thermometers is used as the dry bulb thermometer. The other is used as the wet bulb thermometer. This one is kept wet with gauze applied to a sensing unit and fed with water from a tank. Evaporative heat loss causes the wet bulb to cool. There is a relationship between the amount of water vapor in the air and the temperature marked by a wet and dry bulb thermometer. This relationship is used to determine the humidity.

To automatically observe the vertical distribution (profile) of temperature and humidity, platinum resistance thermometers and sheathed thermocouple thermometers are most commonly used. The Assman ventilated psychrometer incorporates a mercury thermometer, which makes the unit portable. It also has high measurement accuracy. For these reasons, it is used as a handy calibration instrument.

Dew-point hygrometers

Taking advantage of the electric conductivity of lithium chloride, which is highly hygroscopic, this hygrometer indicates the resistance value in response to the dew-point temperature. Under high-humidity conditions, it is capable of continuous measurement with high accuracy. This makes it well-suited to observation in snowy areas. However, it cannot function in low humidity, where the equilibrium temperature is below the atmospheric temperature. Dew-point hygrometers of a cooling type are relatively expensive. In this instrument, a mirror placed in the air is cooled and temperature is measured when frost forms on the mirror surface.

Polymeric humidity sensors

Moisture sensors made of polymeric organic substances measure humidity by detecting changes in electrical properties of polymer membranes in response to changes in atmospheric water content. The leading instruments are those in the HMP45 series (discontinued model, replaced by HMP155) marketed by Vaisala, Oyj., Finland (Photo 3.4-1). Although requiring an external energizer, they are small enough to be equipped in a radiosonde. Because of their easy maintenance in comparison with that for wet and dry bulb thermometers, they are used for continuous observation. There are a few things that need to be kept in mind: the sensor response time of about 15 seconds is slightly longer than that of other sensors; the sensor reads “100 %” continuously and takes time to recover once condensation forms on the sensing unit.

Photo3.4-1 A thin-film polymeric humidity sensor and a platinum resistance thermo sensor in HMP45D (Pt100).

Infrared hygrometers

The hygrometer operates by sensing the infrared absorptivity of water vapor, which gives it a fast response time. The instrument needs to be maintained and calibrated frequently, as its cell is prone to smudging during the observation of high-humidity air. (See Section 2.2 “Open-path CO_2/H_2O gas analyzers” and 2.3 “Closed-path CO_2 gas analyzers” for details.)

Measuring method

As dirt on the web bulb of a wet-and-dry-bulb thermometer prevents water from evaporating evenly, which causes large errors, the gauze needs to be changed periodically. In preparing gauze for a wet-and-dry-bulb thermometer, it has to be boiled well enough to remove accretions such as starch and oil, and then it has to be dried cleanly. The use of distilled water is desirable to moisten the gauze, and the wet bulb should always be kept wet with a thin film of water. The wet bulb sensing unit is positioned approximately 2 cm above the tank water surface, and the water level is maintained constantly. Periodical maintenance is also required to keep the dry bulb from collecting dirt and water droplets.

The polymeric humidity sensor has its sensing unit stored in a resin case which is equipped with a dust filter to protect the sensor. Attention should be paid to dirt on the dust filter and the sensor. Distilled water can be used to remove stubborn dirt. A humidity measuring chip is particularly fragile, and it has to be handled with great care.

As is true for temperature measurement, dirt caught in the shelter should be removed regularly.

The cell of an infrared hygrometer has to be kept clean with regular maintenance using a sponge and 50 % ethanol. If a closed-path hygrometer is connected with a tube to intake air samples, the tube needs to be regularly inspected, cleaned and replaced to prevent leakage, staining, internal condensation and intrusion of rainwater.

Instrumental errors between hygrometers are more pronounced than those between thermometers. To measure the vertical distribution of average humidity, it is recommended that air samples be collected from each elevation and measured with the same analyzer. This method, however, has the disadvantage of not being able to carry out continuous measurement at one point. Also, it is relatively difficult to provide maintenance in a remote place. For these reasons, more than one instrument in the HMP45 series, which is easy maintain, is placed and regularly calibrated at the same elevation.

Tips!

For a ventilated psychrometer, enough gauze should be prepared for frequent replacement. A wash bottle with a capacity of 500 ml may be useful for cleansing gauze and supplying water to the tank.

Tips 3.4-1

Tips!

For easy replacement of the sensory unit, the HMP45 series is designed to be insertable. Structurally, as the cable disconnects when tensed, special care should be directed to wiring. The cable near the sensor may be wound into one or two loops and then fixed.

Tips 3.4-2

Calibration

Active sensors need to be periodically corrected using a reference instrument placed at the same level. Sensors, packing materials and joints that have deteriorated over time must be replaced. To calibrate the reference instrument, a chloride-saturated solution is poured in a test chamber, which is then covered with a lid and left at room temperature for at least one hour so that the test can be carried out under the condition of fixed relative humidity (Appendix 3.4-2). The test chamber used for the calibration of the HMP45 series is commercially available. With it, instrumental outputs can be adjusted. A humidity-measuring chip and a module can be replaceable.

Appendix 3.4-1: Definitions of humidity

Name [unit]	Conversion	Definition
Water vapor pressure e [Pa]	e.g., Sprung Equation 1)	The partial pressure of water vapor in the humid atmosphere
Saturation vapor pressure e_s [Pa]	e.g., Goff-Gratch Equation 2)	The maximum water vapor pressure the air can hold at a given temperature
Saturation deficit e_d [Pa]	$e_s - e$	The difference between the saturation vapor pressure and the water vapor pressure
Relative humidity ϕ_r[%]	$\frac{e}{e_s}$	Vapor pressure as a percent of the saturation vapor pressure
Specific humidity q [kgkg^{-1}]	$\frac{x}{1+x}$ or $\frac{\varepsilon e}{p-(1-\varepsilon)e}$	The mass of water vapor per unit mass of moist air ε: ratio of molecular weight of vapor to that of dry air, ≈ 0.622
Mixing ratio x [kgkg^{-1}] Absolute humidity in some engineering fields [kgkg^{-1}]	$\frac{\varepsilon e}{p-e}$ or $\frac{q}{1-q}$	The mass of water vapor per unit mass of dry air ε: ratio of molecular weight of vapor to that of dry air, ≈ 0.622
Absolute humidity ϕ_a [kgm^{-3}] Vapor density in some engineering fields [kgm^{-3}]	$\frac{0.00794e}{1+0.00366(T_a-273.15)}$	The mass of water vapor per unit volume of moist air
Percentage humidity ϕ_p (saturation) [%]	$100\frac{x}{x_s}$	The ratio of the absolute humidity in moist air to the mixing ratio in saturated air (x_s), expressed as a percentage
Dew point temperature C_{dp} [°C]	Approximation 3) (Hayashi, 1988)	The temperature at which cooled moist air becomes saturated (i.e., condensation starts)

1) $$e = e_s - \frac{j(C_d - C_W)p}{755}$$

Where C_d: dry-bulb temperature [°C], C_W: wet-bulb temperature [°C], p: total atmospheric pressure [Pa], e_s: Saturation vapor pressure [Pa] at a wet-bulb temperature C_W and j: constant (0.5 when the wet bulb is not frozen and 0.44 when the wet bulb is frozen).

2) above water surface

$$\log_{10} e_s = 10.79574\left(1-\frac{T_1}{T_a}\right) - 5.02800\log_{10}\left(\frac{T_a}{T_1}\right) + 1.50475\times10^{-4}\left\{1-10^{-8.2969\left(\frac{T_a}{T_1}-1\right)}\right\}$$

$$+0.42873\times10^{-3}\left\{10^{4.76955\left(1-\frac{T_1}{T_a}\right)}-1\right\}+0.78614$$

above ice

$$\log_{10} e_s = -9.09685\left(\frac{T_1}{T_a}-1\right) - 3.56654\log_{10}\left(\frac{T_1}{T_a}\right) + 0.87682\left(1-\frac{T_a}{T_1}\right) + 0.78614$$

Where T_a: absolute air temperature [K] and T_1: triple-point temperature of water (273.16 K).

3) $$C_{dp} = -c_2 \frac{\ln\left(\frac{e}{6.1078}\right)}{\ln\left(\frac{e}{6.1078}\right) - c_1}$$

Where c_1 and c_2: constants (c_1 = 17.2693882 and c_2 = 237.3 above water surface, and c_1 = 21.8745584 and c_2 = 265.5 above ice).

Appendix 3.4-2: Equilibrium relative humidity of air with chloride-saturated solution

	0 °C	5 °C	10 °C	15 °C	20 °C	25 °C	30 °C
KNO_3	97	96	95	95	94	93	92
KCl	88	87	86	86	85	84	-
NaCl	76	76	75	75	75	75	75
$MgCl_2 \cdot 6H_2O$	34	33	33	33	33	33	32

(unit: %)

(Japanese Industrial Standards Committee, JIS Z 8806:2001, Humidity measurement methods)

3.5 Soil temperature and soil heat flux

3.5.1 Soil temperature

The soil temperature near the earth's surface is high in the day and low at night, as a result of solar radiation. Its daily variation is sinusoidal. As the measuring depth increases, the sinusoidal daily variation decreases in amplitude and the phase shifts backwards. Because the litter layer on the ground surface of a forest tends to become thicker and its border with a soil is less clear as one goes deeper into a cold climate region, caution should be exercised in the measuring depth.

Types of instruments

There are three types of thermo sensors for measuring soil temperature: thermocouple, thermistor (Photo 3.5-1) and platinum resistance (Photo 3.5-2). For more details, refer to Section 3.3 "Air temperature". Because soil has a larger time constant than air, there is no need for a sensing unit to be small. It can be made larger to make it more waterproof. This is necessary due to the high water content of soil.

Photo 3.5-1 Thermistor thermometer 107-L, Campbell. (Photograph: courtesy of Climatec, Inc.)

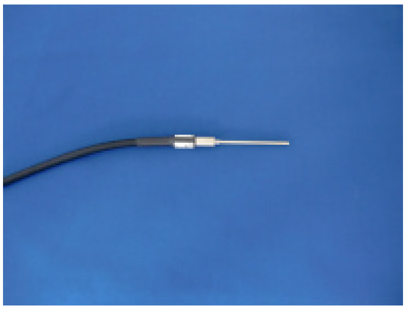


Photo 3.5-2 Platinum resistance thermo sensor C-HPT-5-JM, Climatec. (Photograph: courtesy of Climatec, Inc.)

A thermocouple can be handmade. For soil temperature observation, T-type copper-constantan thermocouples are generally used. To create a thermocouple, compensation lead wire, consisting of a copper wire and a constantan wire, is joined at one end by means of electric welding, silver brazing or soldering. Temperature can be measured by a thermocouple together with a data logger into which a cold junction circuit is built. There are various compensation lead wires of different diameters. Those as thick as a few millimeters are strong and they easily handle the large time constant of soil. The waterproof efficiency of a thermocouple can be enhanced by putting it into a metal pipe that is one size larger than the thermocouple and then adding sealant.

A thermistor is a thermo sensor that takes advantage of the proportionality between temperature and electric resistance of a conductive substance. Because the proportionality factor differs between substances, a thermistor and its connecting logger are usually sold as a pair.

Platinum resistors are basically either three-wire or four-wire. Being little subject to age-related changes, platinum resistors are well-suited for soil temperature sensors that are hard to replace frequently.

The radiation thermometer is another type of instrument that is often used to measure ground surface temperature (Photo 3.5-3). From the surface of any object, longwave radiation corresponding to its surface temperature is emitted. The radiation thermometer captures this longwave radiation, and converts it into temperature to indicate the surface temperature of the object. Despite its advantage of noncontact observation, its accuracy is plus or minus 2 °C, which makes it inferior in accuracy to contact sensors.

Photo 3.5-3 Radiation thermometer IR-SA, CHINO. Right: with telescope attached.
(Photograph: courtesy of CHINO CORPORATION)

Measuring method

The shallower is the soil depth is, the greater are the time variation and vertical change of soil temperature T_s [K]. Thus, thermo sensors need to be placed densely in the shallow layer. As one installation procedure, after a hole is excavated, the thermo sensor is thrust into an undisturbed section of the soil (Photo 3.5-4) and then the hole is refilled. In another method, a narrow vertical hole is dug, into which a thermo sensor is inserted, and the hole is refilled with the same soil. In the former procedure, because the surrounding soil is disturbed, the hole has to be carefully refilled. The latter method is applied to the observation of a shallow layer because it is difficult to ensure that the sensor contacts the soil properly in a deep hole. In either case, the waterproof efficiency of sensors and cables should be taken into consideration.

Photo 3.5-4 Underground section where a thermocouple thermometer (left of the stick) and a soil moisture meter (right of the stick) are embedded. (seasonal forest of Kratie, Cambodia)

One important factor in flux measurement is the temperature of heat/gas exchange surface including ground surface. A method for measuring surface temperature is explained here. To measure surface temperature, the use of a surface thermometer is most convenient and reliable. When surface temperature is measured with a contact thermometer, the sensor should be the smallest possible and it should be installed as close to the surface as possible. The sensing unit is usually installed such as not to be directly exposed to solar radiation.

Tips!

One is often confused about which cable is connected to which sensor after all the sensors are embedded at several depths in a place. It is convenient to attach tags with the information of measuring depth at the ground surface and to the logger junctions for maintenance.

Tips 3.5-1

Tips!

Cables can be laid in a spiral tube or resin pipe for protection against gnawing by mice and other animals.

Tips 3.5-2

Tips!

A waterproof data logger that is equipped with a thermo sensor may perform poorly as a result of condensation on the instrument base. Such malfunction can be prevented by placing silica gel inside the logger and sealing it tightly. The silica gel should be replaced occasionally.

Tips 3.5-3

3.5.2 Soil heat flux

Soil heat flux on the ground surface represents the magnitude of heat exchange between soil and atmosphere, which is expressed in Wm^{-2}. Because soil heat flux is proportional to the temperature gradient at a given depth, it can be calculated on the basis of the vertical profile of soil temperature. However, measurement using a heat flux plate is easier and thus more common.

Instruments

The heat flux plate (Photos 3.5-5 and 3.5-6) operates based on the principle that the temperature difference between the two sides of a thin plate (thermal resistance plate) with a given thermal conductivity is proportional to the amount of passing heat. Heat flux is obtained by dividing the output value of a heat flux plate [mV] by a sensitivity constant $[mV(Wm^{-2})^{-1}]$.

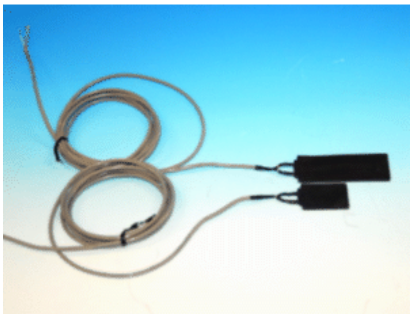


Photo 3.5-5 Heat flux plate PHF-100, PREDE. (Photograph: courtesy of PREDE CO., LTD.)

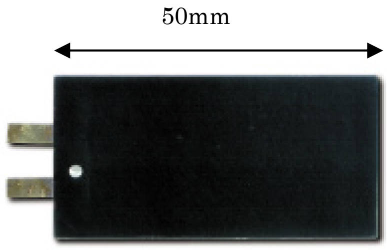


Photo 3.5-6 Heat flux plate MF-180M, EKO. (Photograph: courtesy of EKO INSTRUMENTS CO., LTD.)

Measurement

A heat flux plate should be installed horizontally (Photo 3.5-7). To measure the heat flux of the ground surface, it is better to install the plate at a shallow depth, because the amount of heat stored in the soil above the heat flux plate is ignored. But if the measuring depth is too shallow, errors may occur because the plate prevents water movement and because solar radiation affects measurements. Although there is no determined practice, plates are mostly embedded 1cm to 3cm below the surface. Close contact of the plate with soil should be assured.

Photo 3.5-7 Embedded heat flux plate. (Kawagoe forest meteorology research site)

The method of calculating the heat flux on the basis of temperature change and heat capacity in each soil layer (Equation 3.5-1) is called thermal integration (Fig. 3.5-1).

$$Q = \sum_{n}^{i=1} Q_i + Q_b = \sum C_{v_i} \Delta z_{d_i} \Delta T_{s_i} + Q_b \qquad (3.5\text{-}1)$$

Here, Q: soil heat flux [Wm^{-2}], C_v: volume heat capacity of soil [Jm^{-3}K^{-1}], z_d: thickness of each soil layer [m], T_s: soil temperature, Q_b: soil heat flux at the bottom of the lowest soil layer [Wm^{-2}] and i: subscript indicating soil layer i. The volume heat capacity is strongly affected not only by soil components but also by soil moisture. Therefore, soil moisture measurement is also required.

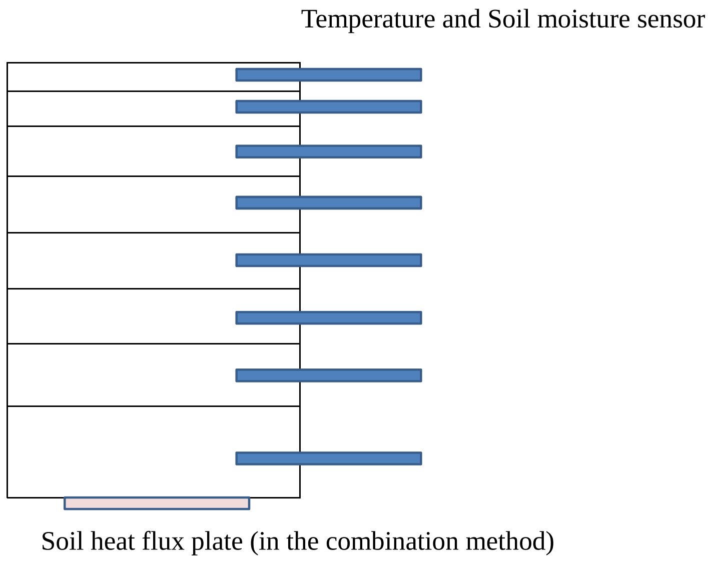


Fig. 3.5-1 Conceptual image of the temperature integration method and the combination method.

3.6 Soil moisture

The two main indexes of soil moisture are volumetric water content θ [m^3m^{-3}] and matric potential Ψ [Pa]. The former is the volume of water as a fraction of the total volume of soil, which is used to obtain an unsaturated diffusion coefficient of soil water. The latter is often referred to in discussions of water absorption by plant roots and soil water movement. There are various sizes of pores in soil. Water caught in smaller pores requires more energy to be extracted. Thus, when soil water is released, the water in large pores is the first to go out. The matric potential represents the amount of energy required for soil pores to hold water in capillary action and adsorption or the amount of energy required by plant roots to draw water in. The value is positive when the soil water is at saturation and negative otherwise. The matric potential per unit volume is expressed in Jm^{-3} = Nm^{-2} = Pa. Hydraulic head ($Jkg^{-1}m^{-1}s^2$ = m), which is a specific measurement of the amount of water energy per unit weight converted into the height of water column, is often referred to as a simple presentation of matric potential. One meter of hydraulic head corresponds to 9.86 hPa.

Other indexes of soil moisture include water content Θ [$kgkg^{-1}$] and saturation ratio η [m^3m^{-3}]. They are obtained from Equations 3.6-2 and 3.6-3, respectively. Soil consists of water, air and soil particles, or a liquid phase, a gaseous phase and a solid phase. The combined volume of the liquid and gaseous phases is the total pore volume.

$$\theta = \frac{V_r}{V_r + V_s + V_a} = \frac{W_r}{V_r + V_s + V_a} \quad (3.6\text{-}1)$$

$$\Theta = \frac{W_r}{W_s} \quad (3.6\text{-}2)$$

$$\eta = \frac{V_r}{V_r + V_a} \quad (3.6\text{-}3)$$

Here, V: volume [m^3], W: weight [g], r: liquid phase, s: solid phase and a: gaseous phase.

Types of instruments

Instruments for measuring the volumetric water content in soil include time domain reflectrometry (TDR) moisture meters such as the CS616-L, produced by Campbell Scientific Inc., US (Fig 3.6-1). On the principle that the permittivity of soil fluctuates according to the volumetric water content, the TDR moisture meter measures the permittivity of soil by the reflection of high-frequency electromagnetic waves. The TDR moisture meter is capable of measuring a wide range of average volumetric water contents for most soil layers as far as the probe reaches. The instrument, however, is susceptible to variations in temperature and soil salinity, which cause some errors. Low-priced permittivity moisture meters whose measurements are based on static capacitors (e.g., EC-5, Decagon Devices, Inc., US, Photo 3.6-1), which have become distributed recently, have similar problems with temperature and soil salinity. The length of the sensing unit varies between sensors, ranging from 5 cm to 1 m. They need to be used properly depending on soil sections.

With the aim of measuring the matric potential, a tensiometer (Photo 3.6-2) is used. The unglazed porous cup, which is filled with deaerated water, is buried to the measuring depth in an augured hole and exposed to the surrounding soil water. The pressure sensor measures the force with which water in the cup is attracted to the surrounding water.

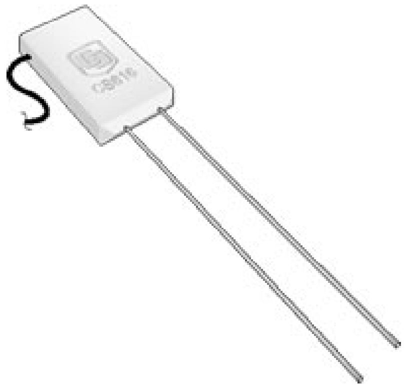


Fig. 3.6-1 TDR moisture meter CS616-L, Campbell. (Illustration: courtesy of Campbell Scientific Inc.)

Photo 3.6-1 Permittivity moisture meter EC-5, Decagon. (Photograph: courtesy of Decagon Devices, Inc..)

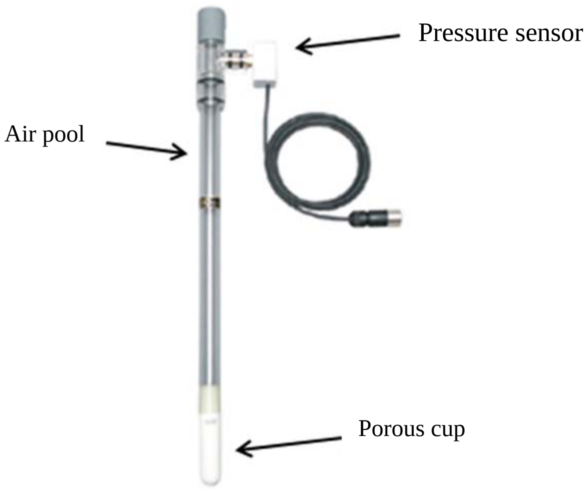


Photo 3.6-2 Tensiometer DIK-3000 series, Daiki Rika Kogyo.
(Photograph: courtesy of Daiki Rika Kogyo Co., Ltd.)

Measuring method

In principle, soil moisture sensors are installed at the same points where soil temperature is measured. In selecting the depth for monitoring soil water flux, water conditions in association with plant roots need to be fully taken into account. For example, in the evergreen forest of the Forestry and Forest Products Research Institute in Kompong, Thom Province, Cambodia, tree roots extend to nearly 2 m below the surface. At this site, observations are carried out at depths of 20, 50, 100, 150, 200 and 250 cm. Because the soil environment is never spatially uniform, it is recommended to repeat observations both area-wise and depth-wise as thoroughly as possible.

The sensing unit of a volumetric water content sensor and the porous cup of a tensiometer should be inserted into soil deep enough so as not to leave a gap at the base. To install the unit in a deeper section, soil is excavated in profile. The unit is inserted horizontally (Photo 3.6-3) and then the soil is recovered. To avoid soil disturbance, a vertical hole is dug to a designated depth with an auger. Then, a sensing unit attached to the tip of an extension rod is inserted into the hole. Any gap around the sensing unit and the porous cup should be filled with soil, because water may otherwise flow into the gap during heavy rainfall.

Photo 3.6-3 Soil profile created for the installation of a soil moisture meter EC-5. (Terrestrial Environment Research Center, University of Tsukuba, Photograph: courtesy of Shinichi Iida, FFPRI)

Caution is required to avoid breaking the porous cup of a tensiometer when it experiences stress while being inserted into soil. As the water in the tensiometer air pool gradually lessens, the air pool needs to be re-supplied with water, when necessary, so that it won't become empty. When supplemented, water in the porous cup is opened up to the atmosphere and it takes one to 24 hours for the sensor to resume a correct value. Caution should be exercised so as to avoid damaging the sensor under excessive pressure when the air pool is capped and installed. The above-ground components, including the pressure sensor, should be shaded from the sun. If they are directly exposed to sunlight and their temperature fluctuates, air expands/contracts in the air pool and temperature drift occurs in the sensor output, which causes significant measurement errors. If the water in the tensiometer freezes, the sensor may stop operating. During the freezing season, observation needs to be suspended, after water is discharged.

With the help of the following soil water characteristic curve equation, the volumetric water content and the matric potential are mutually convertible.

$$\Psi = c_1 \left(\frac{\theta}{\theta_{sat}} \right)^{c_2} \tag{3.6-4}$$

Here, θ_{sat} represents the saturated volumetric water content [m^3m^{-3}], and c_1 and c_2 are constants that can be obtained by the pressure plate method using a pressure plate dehydrator. In the pressure plate method, the lower section of a collected soil sample is exposed to the atmosphere while the upper section is subjected to high pressure, and soil water content is reduced by the pressure difference.

Calibration

The relationships between the volumetric water content and other parameters that are measured directly in soil by a sensor, such as neutron transmittance, electric resistance, thermal conductivity and permittivity, differ a great deal depending on soil components and constituents. Values put out by a soil moisture meter should not be fully trusted but should be corrected with the results obtained by the oven method.

Soil samples must be collected under various wet and dry soil conditions so that a wide range of soil water contents can be obtained. Sampling tubes of 100 cc and 400 cc should be used. After a sample is weighed, it is put in an oven at a temperature of 105 °C so that the water can evaporate. The volumetric water content can be calculated by dividing the weight reduction [g] by the volume of the sampling tube [cm^3]. Comparisons are made between the volumetric water content obtained by the oven method and the measurements made by the sensor to find an approximation. By putting a sensor observation value into the approximation, the volumetric water content can be figured out with reasonable accuracy.

3.7 Precipitation / snow water equivalent (SWE), snow survey (snow depth, snow weight)

Precipitation is the quantity of condensed atmospheric water vapor that is deposited on the earth's surface within a given time, usually expressed in height above a flat surface. Precipitation occasionally distinguishes between rainfall in water form and snowfall in snow form. Although snowfall is the process of solid snow precipitating, its quantity is converted into the amount of water and expressed in mm, as for rainfall.

Snow that does not melt but accumulates on the ground constitutes snow cover. As snow cover exerts substantial effects on the surrounding environment, various observations are carried out on snow cover. This chapter discusses the snow depth and the snow weight.

3.7.1 Precipitation (rainfall / snowfall)

Types of instruments

Tipping bucket rain gauges and standard rain gauges are used commonly for measuring precipitation.

Tipping bucket rain gauge

Rainwater entering from a cylindrical intake mouth is poured through a funnel into a tipping bucket. Precipitation is measured by the tip frequency (Photo 3.7-1).

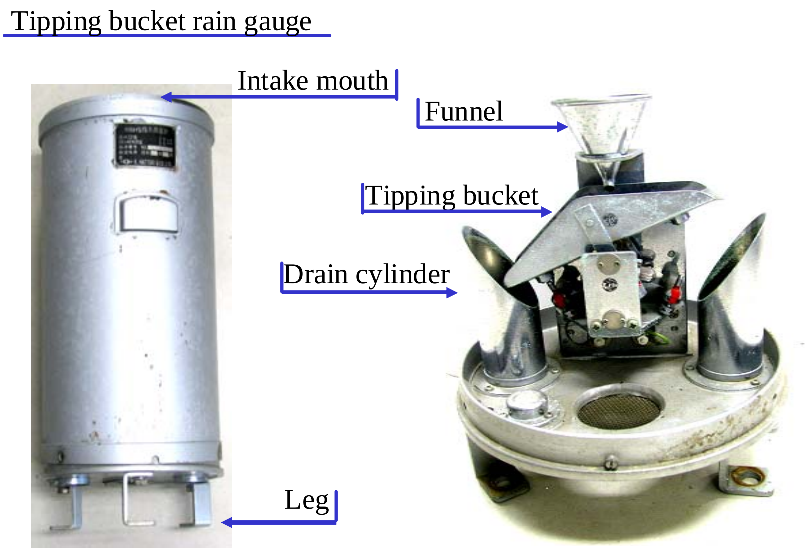


Photo 3.7-1 Appearance and structure of a tipping bucket rain gauge.

Standard rain gauge

A cylindrical water bucket is buried and rainwater entering from the intake mouth is collected in a container within the bucket. The water is then gauged with a graduated measuring cylinder.

As is the case of rainfall, snowfall is measured by a tipping bucket rain gauge, which however requires devices for melting snow and preventing the snow volume from being underestimated under the influence of wind.

Spilt water tipping bucket

To measure snowfall, the bucket is filled with heated water on which snow falls and melts. The amount of water spilt from the bucket is measured by the tipping bucket to determine the water equivalent of the snow. The bucket must be provided with oil regularly to prevent heated water from evaporating from the surface.

Measuring method

A rain gauge must be installed such that it is level and at least four times as far away from any objects (e.g., buildings, trees) as the objects are high. Such a requirement is difficult to satisfy in a forest. To address this problem, trees are usually felled. But in the case where trees are felled, the growth of surrounding trees likely triggers a drastic change in rainfall measurements. For this reason, age-related changes are monitored and effects of environmental changes on installation places are evaluated by placing an auxiliary tipping bucket in the mid-section of a meteorological observation tower, where the observation is little affected by trees, and by carrying out observations at more than one point.

The smooth movement of a tipping bucket rain gauge must be ensured. Pulse data put out at each tip are confirmed. Regular maintenance should be exercised by lubricating junctions and moving parts.

In a snowy region, rain gauges need to be protected from snow by removing snow during the winter or by installing a gauge at a height above the snow cover. When the heater cannot melt snow fast enough to keep up with extremely heavy snowfall, the bucket top may become filled with snow, to which close attention should be paid, particularly in a deep snow-covered area. Once the bucket top is filled up with snow, data are unobtainable for a long time. When heavy snowfall is expected, the heater should be set at a higher temperature.

In seasons other than winter, the spilt water tipping bucket may become infested with bugs if it is filled with water, which hampers operation. Except in winter, measurement should be performed with an ordinary tipping bucket rain gauge.

Tips!

The tipping bucket sends a switch-controlled rectangular-wave signal, which is prone to noise. As a chattering-prevention measure, a small-capacity condenser is put between the two output terminals. Or, to deal with chattering noise, data registered on the data logger continuously in a short time (approx. 1 sec.) can be regarded as one datum.

Tips 3.7-1

Tips!

For snowfall measurement, a windshield should be placed around the tipping bucket to prevent a wind-induced reduction in the catching rate. The size of the windshield is not standardized but depends heavily on the wind velocity and snow quality of the measuring site. In one windy area, for example, the placement of more than one windbreak plate with a height exceeding 2 m was suggested for one tipping bucket. Usually, the reliability of data is significantly improved by enclosing the snow gauge within a cylinder that is two or three times the size of the bucket cylinder and raising its top about 20 cm higher than the bucket.

Tips 3.7-2

Calibration

A tipping bucket is calibrated with water that is gauged using a graduated measuring cylinder. The tipping bucket seldom deviates from the norm enough to need re-calibration.

3.7.2 Snow survey (snow depth, snow weight)

Types of instruments

During a snow season, continuous observation of snow accumulation is practiced extensively to gain information on snowfall.

Snow depth

To visually determine snow depth, a snow gauge is used. Automatic measuring instruments include a laser type and an optical type, in addition to the ultrasonic type that is employed by AMeDAS, Automated Meteorological Data Acquisition System. Ultrasonic sensors and laser sensors are installed above the snow surface to measure the distance from the sensor to the snow surface (Photo 3.7-2). Optical sensors measure the snow depth based on the principle light does not penetrate beyond a certain depth.

Photo 3.7-2 Snow depth measured by ultrasonic snow gauge. (Tohkamachi Experimental Station)

Snow water equivalent

A snow pillow (metal wafer) containing an anti-freezing solution is placed at the measuring site and the snow weight is measured on the basis of the change in pressure on the snow pillow with the help of a snow cover weight meter. As another method, a cylinder of known cross section is inserted into a snow layer down to the soil boundary. Samples collected from all the snow layers are weighed, from which the snow water equivalent is calculated.

Measuring method

As is the case of a rain gauge installation site, snow cover is observed on the level in an area free from obstructions such as trees.

In addition to measurement by a stationary snow gauge, it is desirable to carry out the periodical multi-point measurement using a snow sampler. Through multi-point sampling, spatial variation can be evaluated and the snow density can be determined from snow depth and weight. Although various snow samplers are commercially available, a handmade device can serve the purpose.

When using a snow pillow to measure the snow weight, the measurement weight may often be underestimated as a result of snow bridging over the pillow if the snow volume is too large for the size of the snow pillow. According to past research, it is ideal for the length on a side of a snow pillow to correspond to the maximum snow water equivalent. The length of the snow pillow should be based on expected value of maximum snow weight.

Calibration

Melting snow creates gaps around snow gauging posts and poles, which causes measurement errors. The snow depth should be gauged with a sounding rod, and any necessary measurement corrections must be made.

3.8 Water level, water temperature, irrigation and drainage

In a flooded area or where the groundwater table is high, changes of water level and water temperature substantially affect ground surface characteristics. In an aqueous system with a shallow bottom, the heat capacity of the system increases with increases in the water level. In a high moor, apparent changes in the aerodynamic characteristics and evaporation efficiency of the ground surface are observed along with the rise and fall of the water level. To calculate the heat storage rate of a water body, water level and water temperature must be measured. Abrupt changes in these provide information on the horizontal movement of water. For irrigated farmlands, the amount irrigated or drained for the evaluation of water budget has to be understood beforehand. For some systems, the inflow and outflow of dissolved or non-dissolved carbon and nitrogen that results from irrigation or drainage cannot be ignored in evaluating the water budget for each system.

The water level is the height of the water surface in relation to a reference surface. A method of monitoring a ruler perpendicular to the water surface by visual or by time-lapse camera observation is so fundamental and reliable that it can be applied to the calibration of sensor measurements. There are various water level sensors that operate on different measuring principles. These are used in accordance with the magnitude of the water level fluctuation. These instruments are also used as lysimeters and pans to measure the evaporation rate, and for hydrological observation weirs to measure the flow rate, which is introduced later.

As in the atmosphere, water experiences thermal stratification. As is the case of air temperature (or soil temperature), water temperature measurement needs to take the measuring height (depth) into consideration. Where the water level fluctuates rapidly and substantially, the device must allow the temperature detector to move up and down along with the water level.

A regional estimate of irrigation water is drawn up for a comprehensive irrigation planning. Regarding flux observation on individual paddy lots, a researcher must measure the amount of irrigation and drainage for each lot. In Japan, because farmlands where a land consolidation project has been carried through are irrigated directly from water channels by lot, it is easy to measure the irrigation rate. For drainage, however, water is disposed of not only by surface drainage but also by subsurface drainage through permeation. Accordingly, it is not easy to figure out the drainage rate for farmlands unless underdrain systems such as closed conduits are sufficiently developed.

3.8.1 Water level

Types of instruments

There are two methods of measuring water level. One is to measure the distance from a reference point above the water surface to the water surface; the other is to measure the distance from a reference point below the water surface up to the water surface.

Float water level meter

The water level is determined by the motion of the float. Because the up-and-down motion of a float can be converted into the rotation of a pulley shaft, continuous measurement is possible using a simple instrument. The instrument requires frequent maintenance to ensure its accuracy, as it contains many moving parts.

Ultrasonic water level meter

The distance to the water surface is figured out based on the reflex time of an ultrasonic pulse that is shot at the water surface. The instrument has no moving parts, so it requires little maintenance. Even so, regular inspections must be conducted to ensure that the ultrasonic path is unobstructed. Because acoustic waves are used, corrections may need to be made by understanding the temperature dependence of the acoustic velocity, but a compensation circuit is usually built in to deal with this problem. In some cases in which the difference in temperature between a sensor and a water body like in a well is significant, the compensation accuracy may be less than in conventional cases.

Laser water level meter

A laser is aimed at the water surface, and the distance to the water surface is calculated based on the arrival time of the reflected light. A laser displacement gage is used to obtain measurements in millimeters. If the target water is clear, the laser may penetrate the water instead of reflecting off the water. This can cause error. To prevent this, a plain float is used, with the laser directed to reflect off the float.

Capacitive water level meter

The water level is measured on the principle that the electrostatic capacity between electrodes is proportional to the volume of some fluid. Those that are commercially available have electrodes ranging from 0.5 to 2 m in length. Because the measurement range covered by one sensor is narrower than that of other instruments, fluctuations in water level should be investigated in advance so that the right instrument with an optimal length of electrode can be selected.

Hydrostatic water level meter

This instrument calculates the hydraulic pressure from diaphragm displacement, and then converts it into the water level. The atmospheric pressure needs to be measured simultaneously. However, certain types of instruments require no correction for atmospheric pressure, the negative-pressure side is open to the atmosphere. Inherent to diaphragms is the fact that those with high pressure resistance have poor resolution.

Measuring method

The sensor must be securely fixed to a firm post so that the water current does not cause it to move. When using a large temperature-dependent sensor, devise a sunshade so that solar radiation does not reach the sensor directly. For ultrasonic and laser sensors, protect the sensing volume with a solid pipe or mesh tube to keep objects such as leaves from entering the space between the sensor and the water surface. However, especially in the case of the ultrasonic sensor, the dimensions of the detection area need to be checked in advance in the operation manual or other resources so that the above-mentioned pipe or mesh tube itself does not interfere with the sensing volume. Hydrostatic water depth meters that require atmospheric pressure correction measure the atmospheric pressure in addition to the hydrostatic pressure. If the water depth is too small for a hydrostatic water depth meter to take proper measurements, the apparent water depth can be increased by digging into the bottom surface, inserting a solid pipe, and deploying the sensor in the hole.

The water level and the distance from the reference point to the sensor zero-point are periodically measured and compared with output data of the sensor so that problems of the sensor, if any, can be fixed. At a relatively small body of water, such as a paddy, the water may be blown leeward at times of strong wind. For this reason, the water level at more than one observation point in a paddy needs to be recorded on each visit to the site.

Calibration

Both ultrasonic and laser water level meters can be calibrated indoors, where a proper flat plate is prepared and measurements are taken by varying the distance to the target plate. Among capacitive and hydrostatic water level meters, those for a small range can be calibrated indoors with the help of a water tank or a bucket. For a sensor equipped with a temperature compensation circuit, the accuracy should be confirmed by comparing the output data with the water level that is periodically observed onsite by a researcher.

3.8.2 Water temperature

Types of instruments

As is the case for air temperature and soil temperature, water temperature is measured mostly by thermocouples, thermistors, and platinum resistance thermometers. The characteristics of each are given in Sections 3.3 “Air temperature” and 3.5.1 “Soil temperature”.

Measuring method

To measure water temperature at a constant water depth below the water surface, the sensor is hung from a float. To make measurements at a constant water depth above the water bottom, a weighted sensor is suspended in the water with a float. In either case, the float and the sensor should be covered entirely with a tubular net to prevent wind and current from carrying away the device. Also, caution should be exercised to keep the sensing unit from touching the net.

Photo 3.8-1 Use of a float in measurement of paddy water temperature. (Mase paddy flux site)

Tips!

Before the plants in a rice paddy start growing, the water temperature is relatively uniform because the water bottom serves as a heat source. When plants grow thickly, the water surface serves as a heat source, which allows thermal stratification to occur in the paddy. Measuring the water temperature at more than one depth is useful for analyzing changes in the heat storage flux of a water body.

Tips 3.8-1

Calibration

A water bath is used for calibrating water temperature sensors, in a manner similar to that of air temperature sensors. (See Section 3.3 “Air temperature”.)

3.8.3 Irrigation and drainage

Types of instruments

The flow rate is the basic variable to be measured for studying irrigation and drainage. When the flow rate is approximately 1 to 2 $\mathrm{Lmin^{-1}}$ and there exists a sufficient elevation drop, the flow rate can be directly measured using a bucket, a beaker, and a stop watch. However, long-term continuous measurement of the flow rate requires the following instruments.

Weir flow meter

Running water is collected in a weir with a rectangular or triangular notch (measuring weir). The flow rate is calculated from the amount of water that spills out of the notch and the water level in the weir (Photo 3.8-2). The water level sensor should be selected according to the weir depth. The relationship between the water level and the flow rate is determined by the notch shape. Flow rate formulas for triangular weirs, that is, weirs with a right triangular-shaped notch, and for rectangular weirs, that is, weirs with a rectangular-shaped notch, are provided in the Japanese Industrial Standards (JIS) (JISK0094: http://www.jisc.go.jp/). For irrigation and drainage measurements, a tank with a notch is usually deployed. For example, in direct irrigation from a pipeline, water flowing out of the spigot is stored temporarily in this tank, and the water level in the tank is measured.

Parshall flume flow meter

Parshall flume flow meters are also used for open channel flow rate measurements. The Parshall flume is a Japanese hand-drum shaped structure, and the flow rate is measured using the property that the water surface becomes elevated within the narrow segment of the flume (Photo 3.8-3). Because the configuration of the Parshall flume does not allow much dirt to accumulate, it requires less maintenance than tank style weirs.

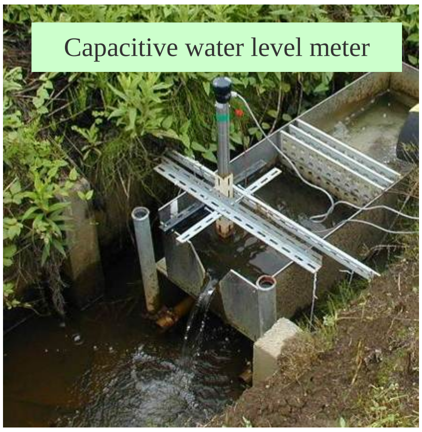


Photo 3.8-2 An example of drainage discharge measurements with the use of a tank style weir (triangular weir). (Mase paddy flux site)

Photo 3.8-3 An example of installation of a Parshall flume for the measurement of the flow rate of an open channel flow. (Photograph: Courtesy of Senecom, Inc.)

Water meter

If the maximum flow rate within a pipeline is on the order of the flow rate of tap water, a propeller type water meter can be used. A paddlewheel water meter, which is frequently used for household applications, is simple in its construction, low in price (a few thousand yen each), and rarely breaks down. However, agricultural water is not free of objects and impurities such as algae, which can cause the water meter to breakdown. Therefore, water meters are often not well-suited for use in agricultural water. As for electromagnetic water meters, they are expensive, however, they contain no moving parts, giving them a broader range of application than propeller type water meters. Finally, warranty conditions need to be reviewed for both types of water meters as the use of drinking water is presumed by the manufacturers.

Measuring method

Initially, 1) the types of irrigation and drainage at the field and 2) the locations of the intake or drainage outlet and the elevation drop need to be assessed. If the head drop between the intake or drainage outlet and the water surface is large, install a tank style weir in that space. If there is sufficient water pressure inside the pipeline, install the tank near the water outlet and introduce water into the tank with a hose. For deployment of a Parshall flume, set it directly in an open channel. If the channel width is larger than the flume inlet width, the channel needs to be narrowed gradually from the upstream region to the flume inlet by creating an embankment or using other means. Therefore, in general, a Parshall flume is not well-suited for use in a concrete channel. Regardless of whether a weir or a Parshall flume is used, it needs to be deployed as designed (usually horizontally) in order to accurately calculate the flow rate from the water level. Furthermore, a weir must be securely anchored to a scaffolding pipe or other object so that it will not be shifted by the water flow. In this procedure, the flow rate during heavy rainfall and the weight of the weir full of water need to be thoroughly taken into consideration. As for water meters, they should be installed directly to spigots with reducer or increaser pipes or similar devices as necessary. The water level in a weir or a Parshall flume should be measured at 10 to 30 minutes intervals using a capacitive or hydrostatic water level meter. As auxiliary data, record the irrigation and drainage conditions during each site visit.

Calibration

Prior to the use of an unconventional weir, create a water-level-discharge curve by evaluating the relationship between the water level and the discharge based on measurements. For measuring the flow rate, water that flows out of the weir within a given time interval should be collected in a bucket, and the collected water should be subsequently measured with a graduated cylinder. When employing a water level sensor, calibration needs to be performed in advance with the above-mentioned calibration procedure for water level sensors. It is also effective to check the water level and flow rate outputs while the sensor is deployed at the site.

3.9 Data logger

Unlike in the case of using the turbulent fluctuation method to measure flux (Chapter 2), micro-meteorological observations require no high-speed sampling data loggers. Data loggers are chosen by taking into account factors such as kinds of signal output from the sensors and power consumption.

Types of instruments

Data loggers are roughly classified into two types: a multi-channel type that handles various output signals (e.g., voltage and pulse) sent from a sensor; and a single-function type that is equipped with a sensor or that registers one kind of signal.

Multi-channel data loggers are commercially available from many manufacturers in various styles, among which are the CR800 and CR1000 (both by Campbell Scientific Inc., US); the CADAC2 (previous model) and CADAC21 (both by Eto denki Coporation, Japan); and; GL220 and GL820 (both by GRAPHTEC Corporation, Japan). The CR1000, CADAC21 and GL-820 are introduced below.

CR1000

Its power consumption is quite low (0.6 mA for a 1 Hz sampling). Its memory capacity is 4 MB. With an optional compact flash (CF) module (CFM100), data can be stored on a CF card. It communicates with a PC through RS-232C or a dedicated cable (optional) to recover data, transfer control programs and adjust settings by means of specific software. The logger is able to respond to digital output sensors. Under a command of a programming language called CRBasic, the measuring interval and applied voltage are controlled at ease. The logger is so versatile and extensible as to increase the number of channels and to achieve relay control simply by adding options.

CADAC21

To activate the logger, a scan unit (MODEL 9220A ~ 9223A) is connected to the main unit (9201A). Through RS-232C or an Ethernet connection (optional at shipping), the logger communicates with a PC for unit control and data transmission. The memory capacity is 8MB. If there are many measuring channels, the volume of data may be excessive, in which case the data can be saved on an always connected PC. With additional scan units, up to 80 measuring channels are available. Measuring intervals can be adjusted with the help of supplementary software. Even beginners are able to handle the logger without difficulty.

GL820

A stand-alone logger has 20 channels and it is scalable up to 200 channels. It is competitive in price comparing to the above mentioned two loggers however its measurement accuracy can be low depending on types of input signals.

Many handy single-function loggers are commercially available at reasonable prices. The Data Mini series (Hioki E.E. Corporation, Japan) is introduced briefly below.

Data Mini

There are several models of Data Mini, such as the VOLTAGE LOGGER 3635 (discontinued model), LR5041, LR5042, LR5043 and the Pulse Logger LR5061. Some are equipped with temperature and humidity sensors (TEMPERATURE LOGGER 3632, LR5011 and LR5001); thus, different loggers can be used for different tasks. Measuring intervals can be adjusted easily by the button on the face of the logger or by the software provided by the manufacturer. To recover data, however, they have to be collected from each logger; by means of a dedicated data collector, COMMUNICATION BASE 3911, 3912, COMMUNICATION ADAPTER LR5091 and DATA COLLECTOR LR5092; and fed into a PC.

Tips!

To carry out measurement extensively using a small output sensor such as a PAR sensor, the VOLTAGE LOGGER 3645 (discontinued model) is used. Setting the measuring range to 50 mV (indicated resolution of 0.01 mV) and turning off the preheat signal function realize cost-effective multi-point observations with a short cable.

Tips 3.9-1

Selection point

Generally the output range of pyranometers and other radio meters such as PAR sensors is as low as between 0 and 10mV. Data loggers that have accuracy to accord with them should be selected. The quantum sensor (LI-190B) produced by LI-COR, Inc., US, for example, has a voltage output range between 0 and 10 mV, which corresponds to between 0 and 3,000 μmolm^{-2}s^{-1} of photons. If a given data logger has a resolution of 1mV, its physical value is equivalent to a resolution of only 300 μmolm^{-2}s^{-1}. Thus, a data logger with a resolution of 0.01 mV or so must be chosen.

In order to take advantage of measurement precision of a sensor, its measurement accuracy as well as its resolution should be taken into consideration.

Some instruments, such as resistance thermometers, need applied voltage and preheating (to turn on the electricity for a few seconds before measurement). For these instruments, loggers capable of controlling applied voltage and preheating should be selected to facilitate measurement and reduce power consumption.

Related information for chapter 3

Further reading

AsiaFlux Steering Committee (ed.) (2007) Practice of flux observations in terrestrial ecosystems. (http://www.asiaflux.net/members/material.html ; available exclusively for AsiaFlux members. It is the English translated edition of AsiaFlux Steering Committee (ed.), 2003, 陸域生態系における二酸化炭素等のフラックス観測の実際.)

Forest environmental survey editorial committee (ed.) (1999) Handbook of forest environmental survey - environmental measurement in forest-, 284pp, Hakuyusha [in Japanese]

Hokkaido branch of Japanese Society of Snow and Ice (ed.) (1991) Procedures for measurement of snow and ice cover, 244pp, Hokkaido University Press. [in Japanese]

Japanese Industrial Standards JIS Z 8806 (2001) Humidity - Measurement methods, Japanese Standards Association

Kondo J. (ed.) (1994) Meteorology in water regime – water and energy balance on land surface-, 348pp, Asakura shoten. [in Japanese]

Kanto Branch of the Society of Agricultural Meteorology of Japan (ed.) (1988) Instruments and measurement techniques in agricultural meteorology, 322pp, Association of advancement of agricultural science [in Japanese]

Kanto Branch of the Society of Agricultural Meteorology of Japan (ed.) (1997) New edition: Instruments and measurement techniques in agricultural meteorology, 356pp, Association of advancement of agricultural science. [in Japanese]

The society for the study of species biology (ed.) (2003) Introduction to plant physiological ecology, 319pp, Bun-ichi Sogo Shyuppan, Tokyo. [in Japanese]

Suzuki N. (ed.) (1996) Meteorological Research Note No.185, Meteorological Instruments: Surface Observation, 155pp, The Meteorological Society of Japan. [in Japanse]

Tsukamoto O. and Monji N. (ed.) (2001) Meteorological Research Note No.199, Methodology of flux measurement on the ground, 242pp, The Meteorological Society of Japan. [in Japanse]

Watanabe I. (ed.) (1987) Experimental method in agricultural environment -Agricultural meteorology and environmental engineering in agriculture-, 285pp, Science House. [in Japanese]

Yoshino M., Asai T., Kawamura T., Shitara H., Nitta T. and Maejima I. (1986) Dictionary of climatology and meteorology, 742pp, Ninomiya Shoten. [in Japanse]

Devices and instruments

Model number in *italic* indicates previous or discontinued model.

3.1

Pyranometer

・ EKO INSTRUMENTS CO., LTD., Japan (MS-802, MS-402, MS-601, ML020VM)

http://www.eko-usa.com/

- Hukseflux Thermal Sensors B.V., The Netherlands (SR11, LP02)
  http://www.hukseflux.com/
- Kipp & Zonen B.V., The Netherlands (CMP 21, CMP 6, CMP 3, SP Lite2)
  http://www.kippzonen.com/
- PREDE CO.,LTD, Japan (PCM-01) http://www.prede.com/file-32html.htm
- THE EPPLEY LABORATORY, INC., US (PSP) http://www.eppleylab.com/

Pyrheliometer

- EKO INSTRUMENTS CO., LTD., Japan (MS-56, *MS-101D*)
  http://www.eko-usa.com/
- THE EPPLEY LABORATORY, INC., US (NIP) http://www.eppleylab.com/
- Kipp & Zonen B.V., The Netherlands (*CH 1*, CHP 1) http://www.kippzonen.com/

Sun tracker

- EKO INSTRUMENTS CO., LTD., Japan (STR-21, STR-22)
  http://www.eko-usa.com/
- THE EPPLEY LABORATORY, INC., US (SMT-3, ST-1, ST-3)
  http://www.eppleylab.com/
- Kipp & Zonen B.V., The Netherlands (SOLYS 2, 2AP)
  http://www.kippzonen.com/

  PREDE CO., LTD, Japan (ASTX-2) http://www.prede.com//file-32html.htm

Shadow band

- Kipp & Zonen B.V., The Netherlands (CM 121B, CM 121C, SOLYS 2, 2AP)
  http://www.kippzonen.com/
- PREDE CO.,LTD, Japan (PSB-100, PRB-100) http://www.prede.com/file-32html.htm
- THE EPPLEY LABORATORY, INC., US (SBS, SDK)
  http://www.eppleylab.com/

Infrared radiometer

- EKO INSTRUMENTS CO., LTD., Japan (MS-202) http://www.eko-usa.com/
- THE EPPLEY LABORATORY, INC., US (PIR) http://www.eppleylab.com/
- Kipp & Zonen B.V., The Netherlands (CGR 3, CGR 4)
  http://www.kippzonen.com/

Net pyrradiometers and four-component net-radiation sensor

- EKO INSTRUMENTS CO., LTD., Japan (MF-11, MR-60)
  http://www.eko-usa.com/
- Hukseflux Thermal Sensors B.V., The Netherlands (NR01)
  http://www.hukseflux.com/
- Kipp & Zonen B.V., The Netherlands (NR Lite2, *CNR 1*, CNR 2, CNR 4)
  http://www.kippzonen.com/
- Radiation and Energy Balance Systems, Inc, US (Q*7) or Campbell Scientific, Inc., US (Q7.1)
  http://www.campbellsci.com/

Spectroradiometer

- EKO INSTRUMENTS CO., LTD., Japan (MS-700) http://www.eko-usa.com/
- ASD Inc., US (FieldSpec Handheld2) http://www.asdi.com/
- THE EPPLEY LABORATORY, INC., US (PSP) http://www.eppleylab.com/

PAR sensors

- LI-COR, Inc., US (LI-190) http://www.licor.com/
- EKO INSTRUMENTS CO., LTD., Japan (ML-020P) http://www.eko-usa.com/
- Kipp & Zonen B.V., The Netherlands (*PAR Lite*, PQS 1) http://www.kippzonen.com/
- KOITO ELECTRIC INDUSTRIES, LTD., Japan (IKS-27) http://www.koito-ind.co.jp/eco/koito-environ/
- PREDE CO.,LTD, Japan (PAR-01) http://www.prede.com//file-32html.htm
- Skye Instruments Ltd, UK (SKP 215) http://www.skyeinstruments.com/

3.2

Vane anemometer

- R. M. Young Company, US (Model 12005 Microvane & 3-Cup Anemometer, Model 05103 Wind Monitor) http://www.youngusa.com/

Wind vane

- Makino Applied Instruments Inc., Japan (VR536) http://business1.plala.or.jp/manox/ [in Japanese]
- Yokogawa Denshikiki Co., Ltd., Japan (A-802) http://www.yokogawa.com/jp-ydk/ [in Japanese]
- Windspeed Limited trading as Vector Instruments, UK (W200P) http://www.windspeed.co.uk/

Anemometer

- Makino Applied Instruments Inc., Japan (AF750) http://business1.plala.or.jp/manox/[in Japanese]
- Yokogawa Denshikiki Co., Ltd., Japan (A-702) http://www.yokogawa.com/jp-ydk/ [in Japanese]
- Windspeed Limited trading as Vector Instruments, UK (W100 Series) http://www.windspeed.co.uk/

Ultrasonic anemometer

- R. M. Young Company, US (Model 85000 Ultrasonic Anemometer) http://www.youngusa.com/
- Vaisala Oyj, Finland (WMT700 WINDCAP) http://www.vaisala.com/
- Gill Instruments Ltd., UK (WindSonic) http://www.gill.co.uk/

Pitot tube

- Okano Works, Ltd, Japan http://www.okanoworks.com/en/main_en.html

Differential pressure gauge

- Setra Systems, Inc., US (Model 239) http://www.setra.com/tra/

3.3

Platinum resistance thermometer

- Vaisala Oyj, Finland (*HMP45A*, *HMP45D*) http://www.vaisala.com
  HMP45A and HMP45D output value in voltage and temperature respectively. HMP45 has been replaced by HMP155 Humidity and Temperature Probe since March 2009.
- Kawaso Electric Industrial Co., Ltd, Japan (Sheath thermo resistance)
  http://www.kawaso.co.jp/en/
- Hayashi Denko co. ltd., Japan (Platinum resistance thermometer element)
  http://www.hayashidenko.co.jp/en/

Thermocouple thermometers

- Grant Instruments (Cambridge) Ltd , UK (CS-U-VL50-0)
  http://www.grant.co.uk/
- CLIMATEC Inc., Japan (Ct-0.32) http://www.weather.co.jp/ [in Japanese]
- Hayashi Denko co. ltd., Japan (Sheathed thermocouple)
  http://www.hayashidenko.co.jp/en/

Thermistor

- Campbell Scientific, Inc., US (107-L) http://www.campbellsci.com/
- Onset Computer Corporation, US (HOBO) http://www.onsetcomp.com/
  Thermocouple type of HOBO (HOBO U12 thermocouple logger) is also available.
- T&D Corporation, Japan (Thermo recorder Ondotori)
  http://www.tandd.co.jp/ [in Japanese]
  Platinum thermometer type of Ondotori (Ondotori Pt) is also available.
- HIOKI E.E. CORPORATION, Japan (TEMPERATURE LOGGER 3632)
  http://www.hioki.com/
- TATEYAMA KAGAKU INDUSTRY Co.,Ltd, Japan (D717)
  http://www.tateyama.jp/eng/

Radiation thermometer

- CLIMATEC Inc., Japan (C-IRR-P) http://www.weather.co.jp/ [in Japanese]
- NEC Avio Infrared Technologies Co., Ltd., Japan (Infrared thermograph)
  http://www.nec-avio.co.jp/jp/products/ir-thermo/en/

Shelter

- CLIMATEC Inc., Japan (CPR-AS-1, vertical type) http://www.weather.co.jp [in Japanese]
- PREDE CO.,LTD, Japan (PFH-01) http://www.prede.com/file-32html.htm
- EKO INSTRUMENTS CO., LTD., Japan (MH-120) http://www.eko-usa.com/
  http://www.eko.co.jp/eko/a/a08-fr.html [in Japanese]

Unit water bath, Low temperature water bath unit

- TAITEC Co., Ltd., Japan (Thermominder SX-10R, Cool bath CB-40)
  http://e-taitec.com/

3.4

Ventilated psychrometer

- PREDE CO.,LTD, Japan (PFH-01) http://www.prede.com/file-32html.htm
- CLIMATEC Inc., Japan (CPR-AS-1/2) http://www.weather.co.jp/ [in Japanese]
- EKO INSTRUMENTS CO., LTD., Japan (MH-120) http://www.eko-usa.com/
  http://www.eko.co.jp/eko/a/a08-fr.html [in Japanese]

Dew-point hygrometer

- Yokogawa Denshikiki Co., Ltd., Japan (E-771) http://www.yokogawa.com/jp-ydk/

Polymeric humidity sensor

- Vaisala Oyj, Finland (*HMP45A*, *HMP45D*) http://www.vaisala.com

  HMP45 has been replaced by HMP155 Humidity and Temperature Probe since March 2009. This new sensor is protected with a sintered PTFE filter therefore having a longer response time (90%, 60sec) and the probe is larger (40mm in diameter and 279mm in length) thus compatibility should be carefully considered when replacing the old model.

Infrared hygrometer

- LI-COR, Inc., US (LI-840, LI-7000, LI-7500) http://www.licor.com/

3.5

Thermistor

- Onset Computer Corporation, US (S-TMA) http://www.onsetcomp.com
- Campbell Scientific, Inc., US (107-L) http://www.campbellsci.com/

Platinum resistance

- CLIMATEC Inc., Japan (C-HPT-5-JM) http://www.weather.co.jp [in Japanese]

Radiation thermometer

- CHINO Corporation, Japan (IR-SAB) http://www.chino.co.jp/english/

Heat flux transducer

- PREDE CO.,LTD, Japan (PHF-100L) http://www.prede.com/file-32html.htm
- EKO INSTRUMENTS CO., LTD., Japan (MF-180M)
  http://www.eko-usa.com/

3.6

Soil moisture sensor

- Decagon Devices, Inc., US (EC-5 ,Capacitance/Frequency Domain Method)
  http://www.decagon.com
- Campbell Scientific, Inc., US (CS616-L, Time Domain Reflectrometry Method)
  http://www.campbellsci.com
- Stevens Water Monitoring Systems, Inc., US (Hydra Probe Soil Moisture and Salinity Sensor , Amplitude Domain Reflectrometry Method) http://www.stevenswater.com
- Delta-T Devices Ltd, UK (ML2x) http://www.delta-t.co.uk
- Sentek Pty Ltd, Australia (EnviroSCAN) http://www.sentek.com.au/

Tensiometer

- Daiki Rika Kogyo Co., Ltd., Japan (DIK-3042) http://www.daiki.co.jp/en
- CLIMATEC Inc., Japan (UNSUC CSK-5500EL) http://www.weather.co.jp [in Japanese]
- UIZIN Co.,Ltd, Japan (UIZ-SMT) http://www.uizin.co.jp [in Japanese]

3.7

Tipping bucket rain gauge

- Yokogawa Denshikiki Co., Ltd., Japan (WB0011) http://www.yokogawa.com/jp-ydk/
- Onset Computer Corporation, US (HOBO Data Logging Rain Gauge RG-3n) http://www.onsetcomp.com/

Snow gauge

- Niigata Electric Co., Ltd, Japan (SDM-301s) http://www.snowcon.com/ [in Japanese]
- SONIC CORPORATION, Japan (SL-370) http://www.u-sonic.co.jp/english/
- Campbell Scientific, (Canada) Corp., Canada (SR-50A) http://www.campbellsci.ca/

Snow weight meter

- Niigata Electric Co., Ltd, Japan (MN-301s) http://www.snowcon.com/ [in Japanese]

3.8

Ultrasonic water level meter

- Keyence Corporation, Japan (UD-300 series) http://www.keyence.co.jp/
- General Electric Company, US (PDCR/PTX 1730/1740) http://www.ge-mcs.com/en/

Capacitive water level meter

- Unidata Pty Ltd, Australia (Model: 6521 series) http://www.unidata.com.au/
- Senecom, Inc., Japan (Trutrack series) http://www.senecom.co.jp/ [in Japanese]

Hydrostatic water level meter

- CLIMATEC Inc., Japan (agency of CSTS series) http://www.weather.co.jp/ [in Japanese]

Hydrological observation weir

- Environmental Measurement Japan, CO., LTD., Japan (MIJ-09K) http://www.environment.co.jp/ [in Japanese]
- Senecom, Inc., Japan (Parshall flume) http://www.senecom.co.jp/ [in Japanese]
- IKEDA KEIKI MANUFACTURING, INC., Japan (PF series) http://www.ikeda-keiki.co.jp/ [in Japanese]

Measuring weir in general

- Takeuchi Tekkosho, Japan ph: +81-562-82-7851

3.9

Multi-channel data logger

- Campbell Scientific, Inc., US (CR1000, CR800) http://www.campbellsci.com/
- Etodenki Coporation, Japan (*CADAC2*, CADAC21, CADAC3) http://www.etodenki.co.jp/ [in Japanese]

- GRAPHTEC Corporation, Japan (GL220, *GL800*, GL820)
  http://www.graphteccorp.com/
- HIOKI E.E. CORPORATION, Japan (*MEMORY HiLOGGER 8420*, MEMORY HiLOGGER 8430-20)
  http://www.hioki.com/
- OMRON Corporation, Japan (ZR-RX40A) http://www.ia.omron.com/

Single-function data logger

- HIOKI E.E. CORPORATION, Japan (TEMPERATURE LOGGER 3632, TEMPERATURE LOGGER LR5011, HUMIDITY LOGGER LR5001, PULSE LOGGER LR5061, *VOLTAGE LOGGER 3635/3645*, VOLTAGE LOGGER LR5041/5042/5043) http://www.hioki.com/
- T&D Corporation, Japan (Thermo recorder Ondotori TR-51S/52S, TR-51i/52i, TR-71Ui/72Ui, Precipitation recorder Amembo RF-3, Voltage logger VR-71) http://www.tandd.co.jp/ [in Japanese]
- Onset Computer Corporation, US (Temperature/Relative Humidity Data Logger HOBO U23 Pro v2)
  http://www.onsetcomp.com

RS-232-to-RS-422/485 converter

- Moxa Inc., US (Transio A52/53) http://www.moxa.com/

RS-232-to-USB conversion cable

- I-O DATA DEVICE, INC., Japan (USB-RSAQ5 series)
  http://www.iodata.com/
  http://www.iodata.jp/product/mobile/serial/ [in Japanese]
- RATOC Systems international, Inc., Japan (REX-USB60F)
  http://www.ratocsystems.com/english/
  http://www.ratocsystems.com/products/rs232c.html [in Japanese]

  It can be used for connecting an Ondotori data logger (T&D Corporation) with a PC with a multiple- core CPU.

Parts and supplies (Some examples)

1. Arrestor (SG-GV series): OTOWA Electric Co., Ltd., Japan
   http://www.otowadenki.co.jp/eng/ **[3.1]**
2. Signal circuit arrestor (CN226 series): Fuji Electric Technica Co., Ltd., Japan
   http://www.fe-technica.co.jp/ [in Japanese] **[3.1]**
3. BNC connecter (UG-89/U (40)): HIROSE ELECTRIC CO., LTD., Japan
   http://www.hirose.com/. **[3.1]**
4. Coaxial cable (RG58A/U): Fujikura Ltd., Japan http://www.fujikura.co.jp/eng/ **[3.1]**
5. DC reference voltage generator (3K02): NEC Avio Infrared Technologies Co., Ltd., Japan
   http://www.nec-avio.co.jp/en/ **[3.1]**
6. Digital multi-meter (PC510a): Sanwa Electric Instrument Co., Ltd., Japan
   http://overseas.sanwa-meter.co.jp/ **[3.1]**

7. Ethanol (99.5, 500 ml): Wako Pure Chemical Industries, Ltd., Japan
http://www.wako-chem.co.jp/english/ **[3.1]**
8. Hand auger: Daiki Rika Kogyo Co., Ltd., Japan http://www.daiki.co.jp/en **[3.5, 3.6]**
9. Paper towel, ("Kimwipes", S.Ply 4.4"×8.4" /Bx 280): Kimberly-Clark Corporation, US
http://www.kimberly-clark.com/ **[3.1]**
10. Plastic adhesive tape (0.2 mm×19 mm×10 m): NITTO DENKO CORPORATION, Japan
http://www.nitto.com/ **[3.1, 3.3, 3.4, 3.5, 3.6]**
11. Precision resistance (RNS1/8YCT52A1001Bmetal-film resistor, 0.1% accuracy and 1kΩ resistance): KOA Corporation, Japan http://www.koaproducts.com/english/ **[3.1]**
12. Double-layer slit conduits: PMA AG, Switzerland http://www.pma.ch/pma_com/ **[3.5]**
13. Flexible pipe ("PanaFleki" DM316, φ23 mm): Panasonic Electric Works Co., Ltd., Japan
http://panasonic-denko.co.jp/ [in Japanese] **[3.5]**
14. Regulated DC Power Supplies (PS series): TEXIO, NIKKE TECHNO SYSTEM CO.,LTD., Japan (former Kenwood) http://www.nikketechno.jp/ [in Japanese] **[3.3]**
15. Sampling tube: Daiki Rika Kogyo Co., Ltd., Japan http://www.daiki.co.jp/en **[3.6]**
16. Sealant ("BATHCAULK", 50 g, transparent): CEMEDINECo., ltd., Japan
http://www.cemedine.co.jp/e/ **[3.1, 3.5]**
17. Self-fusing tape ("Hi-Bon" NO.2, 0.5 mm×19 mm×10 m): Hitachi Chemical Co., Ltd, Japan
http://www.hitachi-chem.co.jp/english/ **[3.1, 3.3, 3.4]**
18. Silica gel (Blue coloured, medium grain, 500 g): Kishida Chemical Co.,Ltd., Japan
http://www.kishida.co.jp/english/ **[3.5]**
19. Spiral wrap (RPST-20): HIRAKAWA HEWTECH CORP., Japan
http://www.hewtech.co.jp/e/ **[3.5, 3.6]**
20. Spiral wrap tubing: Waytek, Inc, US http://www.waytekwire.com/ **[3.5, 3.6]**
21. Washing bottle: SANPLATEC CORPORATION, Japan http://www.sanplatec.co.jp/en/ **[3.4]**
22. Weather-resistant banding band (7.4 mm×250 mm, φ2.5-72 mm): HellermannTyton, UK
http://www.hellermanntyton.com/ **[3.3]**

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List of symbols

A	Avogadro's number (6.023×10^{23} mol^{-1})
$APAR$	radiation absorbed by a forest canopy [$\mu molm^{-2}s^{-1}$]
b	empirical coefficient in REA method
c_l	velocity of light (2.9979×10^{8} ms^{-1})
c_s	speed of sound [ms^{-1}]
c_t	actual speed of sound [ms^{-1}]
C	temperature in Celsius [°C]
C_d	dry-bulb temperature [°C]
C_{dp}	dew point temperature [°C]
C_v	volume heat capacity of soil [$Jm^{-3}°C^{-1}$]
C_W	wet-bulb temperature [°C]
d	span length [m]
dP	the difference between total pressure and static pressure [Pa]
$D_{2000.0}$	magnetic declination at 0:00 on Jan. 1, 2000 [°]
e	water vapor pressure [Pa]
e_d	Saturation deficit [Pa]
e_s	Saturation vapor pressure [Pa]
ΔE	thermopile output voltage [mV]
F_c	CO_2 flux [$mgm^{-2}s^{-1}$]
F_g	vertical flux of a trace gas [$mgm^{-2}s^{-1}$]
F_s	CO_2 storage change [$mgm^{-2}s^{-1}$]
F_E	radiant flux density [Wm^{-2}]
$F_{E\lambda}$	radiant flux density of single wavelength λ [Wm^{-2}]
F_Q	molar photon flux density [$molm^{-2}s^{-1}$]
$F_{Q\lambda}$	molar photon flux density of single wavelength λ [$molm^{-2}s^{-1}$]
h	Planck's constant (6.626×10^{-34} Js)
H	sensible heat flux [Wm^{-2}]
H_{body}	sensible heat flux generated at the instrument surface [Wm^{-2}]
H_{op}	sensible heat flux measured by the open-path gas analyzer [Wm^{-2}]
ΔH	Difference of sensible heat flux measured by SAT from one measured by opne-path gas analyzer: $H - H_{op}$ [Wm^{-2}]
J	number of days elapsed since 0:00, Jan. 1
k	thermopile sensitivity [$mV(Wm^{-2})^{-1}$]
k_d	dome coefficient
$L\uparrow$	downward longwave radiation [Wm^{-2}]
$L\downarrow$	downward longwave radiation [Wm^{-2}]

m_c	molecular weight of CO_2 [$kgmol^{-1}$]
m_d	molecular weight of dry air [$kgmol^{-1}$]
m_w	molecular weight of water vapor [$kgmol^{-1}$]
n	the number of measurement heights
p	atmospheric pressure [Pa]
p_c	partial pressure of CO_2 [Pa]
$PAR\uparrow_{above}$	reflected PAR measured above forest canopy [$\mu molm^{-2}s^{-1}$]
$PAR\uparrow_{below}$	reflected PAR measured under forest canopy [$\mu molm^{-2}s^{-1}$]
$PAR\downarrow_{above}$	downward PAR measured above forest canopy [$\mu molm^{-2}s^{-1}$]
$PAR\downarrow_{below}$	downward PAR measured under forest canopy [$\mu molm^{-2}s^{-1}$]
q	specific humidity [$kgkg^{-1}$]
Q	soil heat flux [Wm^{-2}]
Q_b	soil heat flux at the bottom of the lowest soil layer [Wm^{-2}]
R_0	resistances at 0 °C [Ω]
R_{100}	resistances at 100 °C [Ω]
R_d	infrared radiation that passes through a dome [Wm^{-2}]
R_{net}	net radiation [Wm^{-2}]
$S\uparrow$	upward shortwave radiation (reflected solar radiation) [Wm^{-2}]
$S\downarrow$	downward shortwave radiation (global solar radiation) [Wm^{-2}]
t	time [s]
t_1, t_2	time required for an acoustic signal to travel between the transceivers [s]
t_a	culmination time [h]
Δt_f	flux averaging period [s]
t_s	standard time [h]
T	absolute temperature [K]
T_1	triple-point temperature of water (273.16 K)
T_a	air temperature [K]
T_b	sensor body temperature [K]
T_d	dome temperature [K]
T_s	soil temperature [K]
T_v	sonic virtual temperature [K]
T_{vt}	actual sonic virtual temperature [K]
u	wind velocity [ms^{-1}]
v_d	wind velocity component parallel to the path [ms^{-1}]
v_n	wind velocity component normal to the path [ms^{-1}]
V_a	volume of gaseous phase [m^3]
V_r	volume of liquid phase [m^3]
V_s	volume of solid phase [m^3]

w	vertical wind velocity [ms^{-1}]
W_r	weight of liquid phase [g]
W_s	weight of solid phase [g]
x	mixing ratio [$kgkg^{-1}$]
x_s	mixing ratio in saturated air [$kgkg^{-1}$]
z	height [m]
z_d	thickness of a soil layer [m]
z_f	flux measurement height [m]
β	solar zenith angle [°]
γ	longitude [°]
γ_0	meridian [°]
δ	declination of the sun [°]
ε	ratio of molecular weight of vapor to that of dry air
ζ_a	hour angle [°]
ζ_s	solar altitude [°]
η	saturation ratio [m^3m^{-3}]
θ	volumetric water content [m^3m^{-3}]
θ_{sat}	saturated volumetric water content [m^3m^{-3}]
Θ	water content [$kgkg^{-1}$]
λ	wavelength [m]
ρ	air density [kgm^{-3}]
ρ_c	CO_2 mass density [kgm^{-3}] [mgm^{-3}]
ρ_{cc}	CO_2 concentration [$\mu molmol^{-1}$]
ρ_d	dry air mass density [kgm^{-3}]
ρ_g	concentrations of the atmospheric trace gas [mgm^{-3}]
σ	Stefan-Boltzmann constant (5.67051×10^{-8} $Wm^{-2}K^{-4}$)
σ_w	standard deviation of w [ms^{-1}]
φ	latitude [°]
Φ_a	absolute humidity [kgm^{-3}]
Φ_c	percentage humidity [%]
Φ_p	relative humidity [%]
X	temperature in Fahrenheit [F]
Ψ	matric potential [Pa]
ω	$2\pi/365$ or $2\pi/366$
Ω	equation of time [h]
a, c_1, c_2, j, k_1, k_2, k_3, α	constants

Index

List of authors

1.1The Observation site ... NAKAI Yuichiro, FFPRI
MIYATA Akira, NIAES

1.2 Building infrastructure

1.2.1 Obtaining Land-use Permission ... KOMINAMI Yuji, FFPRI
MIYATA Akira, NIAES

1.2.2 Tower construction and maintenance ... SHIMIZU Takanori, FFPRI
MIYATA Akira, NIAES

1.2.3 Electric power supply ... KOMINAMI Yuji, FFPRI
NAKAI Yuichiro, FFPRI

1.2.4 Lightning Surge Countermeasures ... YAMANOI Katsumi, FFPRI

1.2.5 Observation hut ... NAKAI Yuichiro, FFPRI

1.2.6 Other ... NAKAI Yuichiro, FFPRI
MIYATA Akira, NIAES

1.3 Measurement variables ... NAKAI Yuichiro, FFPRI
MIYATA Akira, NIAES

2.1 Ultrasonic anemo-thermometers, SATs ... SHIMIZU Takanori, FFPRI

2.2 Open-path CO_2/H_2O analyzers ... MANO Masayoshi, NIAES

2.3 Closed-path CO_2 analyzers ... YASUDA Yukio, FFPRI

2.4 CO_2 Storage Change ... KITAMURA Kenzo, FFPRI

2.5 Relaxed Eddy Accumulation, REA Method ... MIYAMA Takafumi, FFPRI

2.6 Data Logger ... TAKANASHI Satoru, FFPRI

2.7 Detection and Reduction of Noise ... YAMANOI Katsumi, FFPRI

3.1 Radiation ... MIZOGUCHI Yasuko, FFPRI

Appendix 3.1-1 ... MIZOGUCHI Yasuko, FFPRI
OHTANI Yoshikazu, FFPRI

Appendix 3.1-2 ... MIZOGUCHI Yasuko, FFPRI

3.2 Wind direction / Wind velocity ... TAKANASHI Satoru, FFPRI

3.3 Air temperature ... MIYAMA Takafumi, FFPRI

3.4 Humidity ... MIYAMA Takafumi, FFPRI

3.5 Soil temperature and soil heat flux ... TAMAI Koji, FFPRI

3.6 Soil moisture ... TAMAI Koji, FFPRI

3.7 Precipitation / Snow Water Equivalent, Snow survey ... KOMINAMI Yuji, FFPRI

3.8 Water level, Water temperature, Irrigation and Drainage ... ONO Keisuke, NIAES

3.9 Data logger ... MIZOGUCHI Yasuko, FFPRI
TAKANASHI Satoru, FFPRI

Authors used the following figures and photographs by courtesy of researchers and sensor manufacturers.

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Fig. 2.3-1 ....OHTANI Yoshikazu, FFPRI

Photo 2.4-1, 2.4-2 right, 3.5-7...MIZOGUCHI Yasuko, FFPRI

Photo 2.4-2 left ....YUTA Satoko, FFPRI

Photo 2.4-3 ....TAKAHASHI Yoshiyuki, NIES

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