

## Chapter 4. Micrometeorological Measurements<sup>5</sup>

John Baker<sup>1</sup> and Bruce Kimball (Collaborator)<sup>2</sup> (September 2010)

<sup>1</sup>U.S. Department of Agriculture, Agricultural Research Service, Soil and Water Management Research, St. Paul, MN <sup>2</sup>U.S. Department of Agriculture, Agricultural Research Service, Plant Physiology and Genetics Research Unit, Maricopa, AZ

Weather and climate data sets for all GRACEnet locations will be necessary, both for interpreting other measured field data and for the added value obtained through modeling of C processes. In addition, some sites will collect CO<sub>2</sub> and H<sub>2</sub>O flux data, and more detailed radiation data. It is important to distinguish between weather and climate data. Climatic data are needed for general site characterization and for generating long-term simulated weather variables for modeling. In general, proximity is not as critical as the quality of the data and the length of the record. The nearest weather station for which data are archived at the National Climatic Data Center (<http://www.ncdc.noaa.gov/oa/ncdc.html>) should be sufficient. Standardized methodology (e.g., Easterling et al, 1996) should be used to extract and develop climatic data that are used for GRACEnet purposes.

### **Climate data**

Climate data are expected to include at least the following:

Mean monthly air temperatures (°C)

Annual mean maximum and minimum air temperature (°C)

Total monthly and annual precipitation (mm)

Annual snowfall (mm)

### **Weather data**

Current weather data, needed in conjunction with specific field experiments, must be measured as proximally as possible. Ideally, all research locations will have weather stations on site, or at least sufficiently close that the data will be representative. This criterion is inexact, and varies for different weather variables; as a general guideline it is desirable to have a basic agricultural weather station (Hubbard and Hollinger, 2005) within 2 km of each field research site. In this context precipitation is the most critical parameter. If the nearest weather station is more than 1-2 km distant, it is recommended that a rain gauge be installed on site. A number of states maintain networks of agricultural weather stations that collect and archive hourly and daily weather data (Table 1). These sites provide links for downloading data, as well as site and data descriptions that can be useful resources.

---

<sup>5</sup> Citation: John Baker and Bruce Kimball. 2010. Sampling Protocols. Chapter 4. Micrometeorological Measurements. IN Sampling Protocols. R.F. Follett, editor. p. 4-1 to 4-10. Available at: [www.ars.usda.gov/research/GRACEnet](http://www.ars.usda.gov/research/GRACEnet)

The suggested minimum data set for daily weather should include the following:

- \_ Air temperature maximum (°C)
- \_ Air temperature minimum (°C)
- \_ Average dew point (°C)
- \_ Daily total precipitation (mm)
- \_ Daily total solar radiation ( $\text{MJ m}^{-2}$ )
- \_ Average daily wind speed ( $\text{m s}^{-1}$ )
- \_ Average daily 10-cm soil temperature (°C)

Optional data, that are desirable for many purposes but not deemed absolutely necessary, include the following:

- \_ Wind direction (degrees from north)
- \_ Pan evaporation (mm)
- \_ N deposition, wet and dry
- \_ Rainfall intensity (mm/hr)
- \_ Soil heat flux ( $\text{MJ m}^{-2}$ )
- \_ Soil temperature profile (°C)
- \_ Soil water content profile ( $\text{m}^3/\text{m}^3$ )
- \_ Snow depth (mm)

All instruments should be periodically checked or calibrated. If possible, data should be retrieved and quality-checked on a routine basis so that malfunctions are discovered as soon as possible.

In addition, for detailed mechanistic modeling it may be necessary for some sites to collect weather data with higher temporal resolution, e.g.- 30 minute or hourly. These sets would typically include:

- \_ Air temperature (°C)
- \_ Relative humidity (%)
- \_ Wind speed ( $\text{m s}^{-1}$ )
- \_ Incoming and reflected solar radiation ( $\text{W m}^{-2}$ )
- \_ Net radiation ( $\text{W m}^{-2}$ ) or incoming and outgoing longwave radiation ( $\text{W m}^{-2}$ )
- \_ Soil heat flux ( $\text{W m}^{-2}$ )
- \_ Precipitation (mm)
- \_ Canopy temperature (°C)
- \_ PAR, incoming ( $\mu\text{mol m}^{-2}\text{s}^{-1}$ )
- \_ PAR, reflected ( $\mu\text{mol m}^{-2}\text{s}^{-1}$ )
- \_ Soil heat flux ( $\text{W m}^{-2}$ )
- \_ Radiometric surface temperature (°C)

## Measurement Guidelines

*Air temperature and relative humidity* – These are typically measured with a single instrument, at a height of 3 m above the surface. There are numerous sources for temperature/RH sensors, and they usually are supplied with a housing that shields them from solar radiation. If this is not the case, a housing should be purchased or constructed to avoid substantial errors due to radiant heating or cooling. All other humidity parameters can be computed from temperature (T) and relative humidity (RH) using the following equations (Buck, 1981), where  $e$  and  $e_s$  are the actual and saturation vapor pressures, kPa, and  $T_d$  is the dew point temperature, °C:

$$e_s = 0.611 \exp\left(\frac{17.502T}{T + 240.97}\right) \quad [1]$$

$$e = \frac{RH}{100} e_s \quad [2]$$

$$T_d = \frac{240.97 \ln(e/0.611)}{17.502 - \ln(e/0.611)} \quad [3]$$

Unfortunately, relative humidity sensors sometimes exhibit calibration drift, so they must be periodically checked. Procedures for doing so are given by Baker (2005).

*Wind speed* – This is generally measured with a cup anemometer. Preferably it should be installed at the same height as the temperature/RH sensor, although at some agricultural weather stations wind speed is measured at 10 m. Anemometers are available from a variety of sources and are relatively trouble-free, although the bearings do wear and must be replaced periodically. The primary difference among different models is their stall speed, i.e. – the wind speed below which they do not turn. This can vary from  $0.2 \text{ m s}^{-1}$  to  $0.5 \text{ m s}^{-1}$  or more; for most GRACenet sites those models with the lower stall speed are to be preferred. For sites where low wind speeds are common, or where highest accuracy is desired, ultrasonic sensors may be preferable. Though they are significantly more expensive, they work at much lower wind speeds, have no moving parts to replace, and provide wind direction information as well as wind speed. With cup anemometers, wind direction must be obtained from a separate wind vane.

*Solar radiation* – Solar radiation is received at the Earth in wavelengths from about 0.2 through  $4 \mu\text{m}$ , and is measured with a pyranometer. There are two types: thermopile sensors and quantum sensors. Thermopile sensors are glass-domed instruments that measure the incident irradiance by measuring the temperature difference between a blackened thermopile (a set of multiple thermocouples) and a reference that is either a white-painted surface or an internal cavity. Quantum sensors produce an output voltage that is proportional to the incident photon flux within a

specified spectral region. Since the desired output is an energy flux ( $\text{W m}^{-2}$ ) the calibration of a quantum sensor will be radiation source-specific, i.e. - if it is calibrated against solar radiation it will not provide accurate results under artificial lighting. The principal advantages of a quantum sensor pyranometer are lower cost and less susceptibility to frost and dew relative to glass-domed thermopile pyranometers (Klassen and Bugbee, 2005). Often it is desirable to use a pair of pyranometers to measure both reflected and incoming solar radiation, the ratio of which is known as albedo. For reflected radiation it is critical that the downward facing instrument be exposed to an extended surface of similar composition, to avoid errors due to reflection from extraneous components or surfaces. Upward-facing instruments should have an unobstructed view of the sky, with no reflections from nearby structures. As with all radiation measurements, leveling is crucial, and should be periodically confirmed.

*Longwave radiation* – Also known as thermal radiation, this is radiation at wavelengths beyond  $4 \mu\text{m}$ . It is not commonly measured in agricultural systems. The instrument that is used to measure it, known as a pyrgeometer, is similar in construction to a thermopile pyranometer, but it has a glass dome that is coated with a substance that is opaque to solar radiation (wavelengths below  $4 \mu\text{m}$ ). The upper cutoff wavelength varies among manufacturers, but is typically in the vicinity of  $50 \mu\text{m}$ .

*Net radiation* – There are now a number of commercially available instruments that combine pyranometers and pyrgeometers into a single, 4-component sensor that measures incoming and outgoing solar and longwave radiation. Net radiation can then be computed from the sum of net solar radiation and net longwave radiation (Campbell and Diak, 2005). However, these 4-component radiation sensors are relatively expensive. A commonly used alternative is a net radiometer that has upper and lower sensing surfaces that are both sensitive to both solar and longwave radiation. The output signal is proportional to the difference between the incident radiation on the upper and lower surfaces. These instruments are less than 25% of the cost of a 4-component system, and have been widely used for many years (Cobos and Baker, 2003). The same exposure rules apply to net radiometers and 4-component sensors – ideally the upward facing surface should have an unobstructed view of the entire sky, and the downward-facing surface should be exposed to an extensive, homogeneous surface to the greatest extent possible.

*Photosynthetically active radiation (PAR)* – This is radiation within the  $0.4 - 0.7 \mu\text{m}$  region of the spectrum, encompassing the photons capable of providing the energy for photosynthesis. It is measured with quantum sensors, accurate yet inexpensive instruments consisting of light-sensitive photodiodes that are fitted with a bandpass filter. When PAR sensors are not available, it is estimated as 45% of solar radiation, but the actual ratio can vary considerably depending on cloudiness and solar angle (Klassen and Bugbee, 2005).

*Soil heat flux* – This measurement is usually made with a small plate that consists of a thermopile that responds to the difference in temperature between the upper and lower

surfaces. This gradient is multiplied by the known thermal conductivity of the plate material to calculate the heat flux across it. The plate is constructed of material that has a thermal conductivity similar to that of soil, to minimize convergence of divergence of the heat flux. However, the soil thermal conductivity is not constant since it is affected by the soil water content. Consequently a correction, based on the ratio of plate to soil thermal conductivity, must be applied to the measured heat flux, and this requires a separate measurement of soil water content. The plate should be placed 5 to 10 cm below the surface, with thermocouples in the soil layer above, to avoid the significant distortion of the temperature field that occurs when the flux plate is placed too close to the surface. Replicate measurements should be made if possible, due to the small size of heat flux plates relative to the scale of heterogeneity in surface conditions. Since the plate is actually measuring the heat flux at the depth of installation, and the variable of interest is actually the heat flux at the surface, calorimetry must be used to compute the flux divergence between the surface and the plate depth. This is done by measuring  $dT/dt$ , the time rate of change of the surface layer temperature, which is then multiplied by the heat capacity of the surface layer (Sauer and Horton, 2005):

$$S_0 = S_z + C_v \Delta z \frac{dT}{dt} \quad [4]$$

$S_0$  = heat flux at the surface ,  $W m^{-2}$

$S_z$  = heat flux at the depth of the heat flux plate, usually 5 or 10 cm

$C_v$  = volumetric heat capacity of the soil,  $J m^{-3} K^{-1}$

$\Delta z$  = distance between the surface and the plate, m (e.g. - 0.05 or 0.1 m)

$dT/dt$  = rate of change of surface layer temperature,  $K s^{-1}$

The volumetric heat capacity can be estimated in turn from the surface layer volumetric water content ( $\theta_v$ ), organic matter fraction ( $f_{OM}$ ), bulk density ( $\rho_s$ ,  $kg m^{-3}$ ), the volumetric heat capacity of water ( $C_{v,H2O}$ ), and the specific heats for organic matter ( $C_{p,OM}$ ) and mineral soil ( $C_{p,s}$ ):

$$C_v = \theta C_{v,H2O} + \rho_s [f_{OM} C_{p,OM} + (1 - f_{OM}) C_{p,s}] \quad [5]$$

$$C_{v,H2O} = 4.2 \times 10^6 J m^{-3} K^{-1}$$

$$C_{p,OM} = 2.5 \times 10^3 J kg^{-1} K^{-1}$$

$$C_{p,s} = 800 J kg^{-1} K^{-1}$$

A heat flux system is installed by digging a small pit approximately 15 cm deep. At the desired depth (typically 5 or 10 cm), a slot is cut into the side wall of the pit, and

the plate is inserted into it. Good soil/plate contact is essential, so the slot should be just large enough for the plate to fit in. The thermocouples used for measuring the temperature of the surface layer above the plate can be inserted into holes created with a small screwdriver. The pit should be carefully backfilled to minimize convergence or divergence of heat and water flow.

*Precipitation* – The most common instrument for precipitation measurement is the tipping bucket, in which each tip generates a pulse by closing a switch. Weighing gauges provide a more expensive alternative. For sites where snow is a significant contributor to annual precipitation, special precautions must be taken. If a tipping bucket is used, it must be heated. Weighing gauges must have an antifreeze solution in their collection bucket. In either case, it must be recognized that the gauge will systematically underestimate total precipitation due to wind effects and evaporation from the collection surface. A detailed description of correction procedures for different gauge types can be found in Goodison et al (1998).

*Surface or canopy temperature* – Similar to the pyrgeometer are so-called infrared thermometers (IRTs) which can infer the temperature of a surface by sensing the radiation it emits. They typically sense radiation between 8 and 12  $\mu\text{m}$  because terrestrial surfaces like plant and soil emit highly in this band and especially because the sky emits little radiation in this band (the so-called “atmospheric window”), thereby reducing the confounding effects of reflected sky radiation on the temperature readings. Using the 4<sup>th</sup>-power Stefan-Boltzmann equation, the radiative flux,  $F$  ( $\text{W m}^{-2}$ ), sensed within its waveband by an IRT is:

[6]

$$F = f\varepsilon\sigma T_{Ik}^4 + (1 - \varepsilon)R_L$$

where  $f$  is the fraction of black body radiation emitted within the waveband sensed by the IRT,  $\varepsilon$  is the emissivity of the surface,  $\sigma$  is the Stefan-Boltzmann constant,  $5.67 \times 10^{-8} \text{ W m}^{-2} \text{ K}^{-4}$ ,  $T_{Ik}$  is the temperature inferred by the IRT (K),  $R_L$  is the incoming sky radiation in the waveband of the IRT ( $\text{W m}^{-2}$ ), and  $(1-\varepsilon)R_L$  is the sky radiation reflected from the surface within the bandwidth of the instrument. IRTs are calibrated over blackbody cavities where  $\varepsilon=1$  and the second term can be ignored, producing an equation relating output voltage to  $T_{Ik}$ . The emissivity of most vegetation is about 0.98 and soils are typically greater than 0.91, so an error is encountered under field conditions, but one can obtain reasonable accuracy with the calibrated output (Campbell & Dial, 2005).

However, for more precise work, a correction for reflected sky radiation should be made using:

$$T_{ck} = \left\{ (1/\varepsilon) \left\{ T_{Ik}^4 - [(1 - \varepsilon) \varepsilon_a T_a^4 / f] \right\} \right\}^{(1/4)}$$

where  $T_{ck}$  is the corrected surface temperature (K), and  $\varepsilon_a$  is the emissivity of the air in the waveband of the sensor and the assumption is made that the fraction of radiation in the waveband at both  $T_{ck}$  and  $T_{Ik}$  are the same. The sky emissivity in the 8-14  $\mu\text{m}$

band in the zenith direction,  $\varepsilon_{az}$ , can be calculated from an equation created by Idso (1981b):

$$\varepsilon_{az} = 0.24 + (2.98 \times 10^{-6})e_a^2 \exp(3000/T_{ak})$$

where  $e_a$  and  $T_{ak}$  are the screen-level vapor pressure (kPa) and temperature (K), respectively. Idso (1981a) also derived a correction to convert zenith to hemispherical emissivity:

$$\varepsilon_a = \varepsilon_{az}(1.4 - 0.4 \varepsilon_{az})$$

The fraction of black-body radiation in the 8-14  $\mu\text{m}$  band emitted at temperature  $T_{lk}$  can be computed from (Kimball *et al.*, 1982):

$$f = -0.6732 + (0.6240 \times 10^{-2})T_{lk} - (0.9140 \times 10^{-5}) T_{lk}^2$$

Commercial instruments are generally sensitive to their own body temperature in addition to the viewed surface temperature, so both temperatures must be used in the calibration equation.

Canopy temperature readings can be affected by the proportion of leaves and soil viewed by the instrument. To reduce such effects, IRTs are typically deployed at a meter or more above the surface at oblique angles of 45° or more from zenith so as to view proportionally more vegetation because leaf transpiration is usually more than soil evaporation, and the temperature more representative of the dominate evaporating surface is desired. IRTs are also affected by the sun angles, so if trying to measure small differences among plots in the same experiment, care should be taken to point all instruments in a similar direction, poleward being preferred.

## Flux Data

At some sites it may be possible or desirable to measure net ecosystem exchange of CO<sub>2</sub> (NEP) and H<sub>2</sub>O (ET). This may be done with a Bowen Ratio system or a gradient system, but the most common approach currently employed is eddy covariance (Fig. 1.) This requires fast measurement of fluctuations in vertical windspeed and concentration of the scalar of interest. Both CO<sub>2</sub> and H<sub>2</sub>O can be measured by the same infrared gas analyzer (IRGA), which can be an open-path or a closed-path instrument. Closed path instruments require a pump and some additional signal processing, but are less affected by precipitation. In order to capture all eddies contributing to the flux, signals should be sampled at 10Hz or better. Eddy covariance data should be processed in 30 to 60 minute blocks. Smaller intervals may miss some low-frequency contributions to the flux, while larger intervals risk violation of stationarity considerations (Baldocchi *et al.*, 1988). The common manufacturers of eddy covariance instrumentation provide software for data processing, and there are also freely available public domain packages, such as EdiRe (<http://www.geos.ed.ac.uk/abs/research/micromet/EdiRe/>).

There are a number of site considerations for eddy covariance systems (Meyers and Baldocchi, 2005). The instruments must be mounted high enough above the top of the crop canopy to minimize the wake effects of individual leaves, but must not be so high that they are affected by exchange processes outside the field in which they are installed. The common rule of thumb for the latter requirement, known as fetch, is 100:1, i.e. - the upwind distance to the edge of the field should be at least 100 times the height of the instrument above the exchange surface, although footprint analysis suggests that this guideline is quite conservative; the primary area contributing to the flux is usually much closer, except when the atmosphere is strongly stable. This is most frequently associated with calm nights, and data collected under these conditions are generally screened out, along with data collected when it is raining, since precipitation affects the accuracy of sonic anemometers. Data that are screened out or missing are replaced with gap-filling schemes that use flux and ancillary data collected during valid periods to construct algorithms that take the form of light response functions for daytime photosynthetic fluxes or temperature-based Q10 functions for respiration fluxes (Moffat, et al., 2007). When data are archived, it is essential that modeled or gap-filled values be clearly identified as such to distinguish them from measured values.

Additional data collected at flux measurement sites should, at a minimum, include net radiation, soil heat flux, shallow (e.g.-5 cm) soil temperature, PAR, and precipitation. A range of physiological variables will often add value to flux data, including leaf area index, crop height, growth stage, rooting depth, and canopy radiometric temperature. Additional information on measurement and archival of flux data can be found on the following web sites:

<http://public.ornl.gov/ameriflux/>

<http://www.carboeurope.org/>

<http://www.fluxnet-canada.ca/home.php?page=jobs&setLang=en>

<http://asiaflux.yonsei.ac.kr/>



### Literature cited:

- Baker, J.M. 2005. Humidity. Pp. 31-41 in Hatfield, J.L., and J.M. Baker (eds). 2005. *Micrometeorology in Agricultural Systems*. Agronomy, Madison, WI. 584 pp.
- Baldocchi, D.D., B.B. Hicks, and T.P. Meyers. 1988. Measuring biosphere-atmosphere exchanges of biologically related gases with micrometeorological methods. *Ecology* 69:1331-1340.
- Buck, A.L. 1981. New equations for computing vapor pressure and enhancement factor. *Journal of Applied Meteorology* 20:1527-1532.
- Campbell, G.S., and G. R. Diak. 2005. Net and thermal radiation estimation and measurement. Pp. 59-92 in Hatfield, J.L., and J.M. Baker (eds). 2005. *Micrometeorology in Agricultural Systems*. Agronomy, Madison, WI. 584 pp.
- Cobos, D.R., and J.M. Baker. 2003. Evaluation and modification of a domeless net radiometer. *Agron. J.* 95:177-183.
- Easterling, D.R., T.C. Peterson, and T.R. Karl. 1996. On the development and use of homogenized climate datasets. *J. Climate* 9(6):1429-1434.
- Goodison, B.E., P.Y.T. Louie, and D. Yang. 1998. WMO Solid precipitation measurement intercomparison. WMO Instruments and Observing Methods Rept. #67. World Meteorol. Org.
- Hubbard, K.G., and S.E. Hollinger. 2005. Standard meteorological measurements. *In* Hatfield, J.L., and J.M. Baker (eds). 2005. *Micrometeorology in Agricultural Systems*. Agronomy Monograph no. 47. American Society of Agronomy, Madison, WI. 584 pp.
- Idso, S.B. 1981a. An experimental determination of the radiative properties and climatic consequences of atmospheric dust under non-dust storm conditions. *Atmos. Environ.*, 15:1251-1259.
- Idso, S.B. 1981b. A set of equations for full spectrum and 8-14  $\mu\text{m}$  and 10.5-12.5  $\mu\text{m}$  thermal radiation from cloudless skies. *Water Resources Research* 17:295-304.
- Kimball, B.A., S.B. Idso, and J.K. Aase. 1982. A model of thermal radiation from partly cloudy and overcast skies. *Water Resources Research* 18:931-936.
- Klassen, S., and B. Bugbee. 2005. Shortwave radiation. Pp. 43-57 in Hatfield, J.L., and J.M. Baker (eds). 2005. *Micrometeorology in Agricultural Systems*. Agronomy, Madison, WI. 584 pp.
- Meyers, T.P., and D.D. Baldocchi. 2005. Current micrometeorological flux methodologies with applications in agriculture. Pp. 381-396 in Hatfield, J.L., and J.M. Baker (eds). 2005. *Micrometeorology in Agricultural Systems*. Agronomy, Madison, WI. 584 pp.
- Moffat, A.M., and many others. 2007. Comprehensive comparison of gap filling techniques for eddy covariance net carbon fluxes. *Agric. For. Meteorol.* 147:209-232.
- Sauer, T.J., and R. Horton. 2005. Soil heat flux. Pp. 131-154 in Hatfield, J.L., and J.M. Baker (eds). 2005. *Micrometeorology in Agricultural Systems*. Agronomy, Madison, WI. 584 pp.

Ohio	<a href="http://www.oardc.ohio-state.edu/newweather/">http://www.oardc.ohio-state.edu/newweather/</a>
Illinois	<a href="http://www.isws.illinois.edu/warm/cdflist.asp?typ=a">http://www.isws.illinois.edu/warm/cdflist.asp?typ=a</a>
Iowa	<a href="http://mesonet.agron.iastate.edu/agclimate/index.phtml">http://mesonet.agron.iastate.edu/agclimate/index.phtml</a>
Missouri	<a href="http://agebb.missouri.edu/weather/history/index.asp">http://agebb.missouri.edu/weather/history/index.asp</a>
North Dakota	<a href="http://ndawn.ndsu.nodak.edu/">http://ndawn.ndsu.nodak.edu/</a>
Nebraska	<a href="http://www.hprcc.unl.edu/services/index.php?p=online">http://www.hprcc.unl.edu/services/index.php?p=online</a>
Washington	<a href="http://weather.wsu.edu/">http://weather.wsu.edu/</a>

Table 1. Selected states where agricultural weather network data are archived and made available. Some sites may charge a fee for data.



Figure 1. Eddy covariance system measuring CO<sub>2</sub> and H<sub>2</sub>O fluxes above an irrigated corn field.