Weather Monitoring
IN THE ENVIRONMENT

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Weather monitoring has evolved over the past few centuries from an amateur pastime, traditionally done by country vicars, to a well-organised professional activity spanning the globe, vital for a very wide range of economic, commercial, environmental, military, civil protection and food production purposes. An effective monitoring programme needs to take into account the likely uses to which the information collected will be put. This article is primarily concerned with environmental applications. These include:

Atmospheric pollution: dispersal of pollutants in the atmosphere is driven almost entirely by the weather and so weather information is vital in both monitoring and predicting the course of events. Wind speed and direction, temperature, humidity and rainfall may all be important factors in the processes.
Pollen and seed dispersal: These are affected by much the same factors as atmospheric pollution.
Water resources, water quality and hydrology: Input to hydrological systems in the form of rain is clearly a weather phenomenon, but weather also drives evaporation, plant growth, photosynthesis and transpiration. It also affects chemical transformations in the environment, which may be controlled by temperature, light levels or biological activity.
Ecology: All living organisms are affected by the physical state of their environment, the most important aspects of which are controlled by the weather.
Agriculture: Farming has always been heavily dependent on the weather, both for its control on the quality and quantity of a harvest and its effect on the farmer's ability to work the land or to graze his stock.
Climate change: Weather monitoring is important in defining present climate, in detecting changes in climate and in providing the data to input into models which enable us to predict future changes in our environment.

Requirements For Weather Information in Environmental Studies

Because of the wide variety of uses for the information, there is a similarly wide variety of environmental variables which are of interest to different groups of people. These include solar radiation, photosynthetically active radiation (that part of the electromagnetic radiation spectrum which is necessary for chlorophyll to carry out photosynthesis - often abbreviated to PAR), wind speed, wind direction, barometric pressure, air temperature, humidity (or water vapour pressure), soil heat flux, soil temperature, soil water status, presence of dew and net radiation. The concentration of certain atmospheric constituents may be important in some cases.

The demand for this mass of data, usually on an hourly or more frequent timescale, has been met by the development and widespread deployment of automatic weather stations (AWSs) over the past 30 years or so.

Constraints on Instrumentation

The quality of sensors, and hence the data from them, is constrained by a number of factors, of which the most obvious is finance.

In almost all cases, the sensors, data loggers, telecommunications links, etc. are required to work over a wide range of environmental conditions. The principal problems are caused by ingress of rain, condensation and by the large temperature range (ca. 60 °C) over which the equipment is expected to work.

Power requirements are often a major consideration. In most cases, the cost of providing mains power to an AWS is prohibitive. Also, in many cases, AWSs must be sited in places sufficiently remote from vehicle access that powering the station by large batteries, whilst not impossible, is very difficult and not usually economic. Advances in low power sensors, solar power and battery technology have to a large extent solved the problem. In practice, it is found that the power requirements of an AWS can often be fulfilled indefinitely by a 5 W solar panel and a 7 Ah battery under UK conditions. Many stations, indeed, operate for several months on a few dry cells. However, these power requirements demand that the power taken by individual sensors and by the logger and/or telemetry equipment is such that the average power drain is not more than about 3 W. Such low power demands a specialised environmental data logger. These are available at prices in the region of £2,000 for a complete system and come with relatively sophisticated software for download and data display, usually onto a laptop PC, although similar software running on palmtop computers is becoming available.

Available Sensors

Radiation - There are at least four radiation measurements of interest for environmental applications. The most common is incoming shortwave radiation (mainly in the visible band), which is composed of the direct solar beam and solar radiation scattered by the atmosphere and clouds. Sometimes, these two components are required separately, which can be accomplished by use of a shading ring fitted to one of a pair of solarimeters. Albedo is often of interest, being essentially the reflection coefficient to shortwave radiation of the earth surface at the point of interest. As mentioned above, PAR is needed by workers interested in crop growth and primary production. Lastly, those interested in energy and water balance studies need net radiation, which is the difference in total radiant energy (both shortwave and infra-red) received from above and that reflected or emitted from the earth surface (which includes vegetation growing on it).

High quality commercial radiation sensors all rely on intercepting the radiant energy on a blackened disc and measuring the resulting temperature rise by means of a thermopile. To prevent cooling by wind and air currents, the intercepting surface is usually protected by one or more transparent domes. This can cause its own problems and the accuracy (and hence cost) of radiometers is determined by the materials used for domes, measures taken to control internal air circulation and compensation for ambient air temperature and internal heating. Shortwave sensors normally use glass domes, but this material does not transmit infra-red radiation well and so net radiometers use relatively thin polythene domes. Polythene domes degrade in sunlight, requiring approximately annual replacement, and are vulnerable to being pecked by birds. A recent development in net radiometers is the NR-Lite from Kipp & Zonen. This has no domes, but two blackened, PTFE-coated and slightly conical surfaces, which shed rain efficiently. The lack of domes reduces maintenance requirements considerably, although these sensors are more prone to the effects of wind, and rain and dew on the blackened surfaces.

Cheaper radiation sensors use silicon photocells without protective domes, although these are suitable (because of the silicon band gap) only for shortwave radiation and have a spectral response that matches that of incoming radiation only approximately.

Humidity is normally measured in one of two ways. The most common method is to use a capacitive sensor, which contains a hygroscopic plastic, whose moisture content is measured electrically. These are normally housed in a louvred plastic or aluminium radiation shield. These sensors achieve accuracies of about 1% relative humidity, although they are less accurate close to saturation. Their lifetime is also restricted to about three years. The other main approach to humidity measurement relies on a variation of the traditional wet and dry bulb psychrometer, as used in the traditional Stephenson Screen. The sensors are thermistors or platinum resistance thermometers. The latter are more expensive, but more accurate and stable. Thermometer accuracy to about 0.1 °C is required. At low wind speeds, better measurements are obtained if the psychrometer is aspirated with a small fan, although the power requirement may be a problem. Maintenance is required to keep the water reservoir replenished with distilled or deionised water and to change the wick at approximately fortnightly intervals. Although the psychrometer is capable of giving superior humidity estimates, especially

An aerodynamic raingauge, designed to minimise loss of rainfall catch caused by disturbance of the airflow around it. The tipping bucket mechanism can be seen in the base of the gauge on the left. the magnet which operates a reed switch is mounted in the black rod at the back, attached to the bucket. The switch is in the adjacent black rod. Tips of the bucket (usually occurring when 0.2 mm of rain have fallen) are counted by detecting switch closures. All tipping bucket raingauges use a similar mechanism.

when aspirated and at high humidity levels, scrupulous maintenance is essential.

Air temperature is measured either with a thermistor or platinum resistance thermometer and is usually combined into the humidity measurement sensor.

Rainfall is measured almost universally by a tipping bucket raingauge, a principle reputedly invented by Sir Christopher Wren. These alternately fill one half and then the other of a divided U-shaped container, pivoted about its centre. When the weight of water is sufficient, the bucket tips and empties, allowing the other half to fill. Tips are detected by a reed switch and magnet arrangement. Some mechanisms have only a single-compartment bucket and a counterweight. Snow and ice are the major problems with this type of device (and with almost all raingauges). Heaters, either electrical or gas, can be fitted, but the former are normally too power hungry to use unless mains power is available and the latter are temperamental. Reliable measurements of snow are extremely difficult, owing to its propensity to drift. Traditional deployment of raingauges, mounted with the orifice above ground level, has been shown in many studies to lead to it catching too little rain. This is ascribed to acceleration of the airflow as it passes over the raingauge, sweeping the rain across the orifice, rather then it falling into it. Various designs of wind shield are available. The best solution is, however, generally acknowledged to be to mount the raingauge such that its orifice is level with the ground surface in a shallow (300 mm deep) pit about 1.5 m square. This prevents splash of rain into the raingauge from the surroundings. To ensure that the airflow over the ground is not disturbed, the pit is covered with a mesh (see picture).

Wind measurement is usually accomplished by traditional cup anemometers (although some types use a propeller, which can be directed into the wind and thus measure direction simultaneously) and wind vanes. Rotations of the anemometer spindle are usually counted by means of a magnetically-actuated reed switch or optically. Position-sensing of the wind vane is usually either by a potentiometer connected to the spindle or by a series of reed switches actuated by a magnet attached to the spindle. Solid state anemometers, which can measure wind speed and direction simultaneously by ultrasonic time-of-flight methods, are starting to appear and are becoming competitive in price with more traditional sensors. With no moving parts, these are likely to be more reliable and maintenance-free.

Other sensors commonly found on AWSs measure barometric pressure, soil water and soil heat flux.

Future Developments

The most significant development, which has enabled automatic weather stations to become an everyday item in most environmental studies, has been the development of economical, low-power solid state data loggers. These can be expected to become more versatile, user-friendly and able to record more variables and greater volumes of data at roughly the same or lower price as today.

Sensors have undergone incremental improvement over the years, leading to a steady improvement in performance and reliability accompanied by a fall in price. This trend should continue. Solid state wind sensors are likely to become an economical alternative to cup anemometers and vane wind direction sensors. Similar radical alternatives to other sensors are likely to appear. The number and variety of sensors on weather stations is also likely to increase. Visibility monitors are already starting to appear on road monitoring stations. The most likely additions are those monitoring chemical variables, not only in the atmosphere (e.g. ozone, SO2 and other industrial pollutants), but also in rainfall and even in the soil. Pollen is another constituent whose concentration level is likely to be in demand.

The most significant change, however, is likely to result from developments in communications technologies. These will allow more remote, real-time weather monitoring and access not only to weather information from a limited number of stations owned by the operator, but from networks of stations spread over a wide area. This is, to some extent, already happening.

There has recently been an explosion in the number of weather stations installed in the UK and other countries. Many of these are operated by interested amateur owners (a modern equivalent of the 18th century vicar) and usually feature relatively cheap (a few hundred pounds sterling) stations. The variables measured are normally limited to temperature, humidity, rainfall, wind direction and windspeed. Barometric pressure is sometimes included and, more rarely, solar and /or UV radiation. At least 132 stations operating in the UK and Ireland publish data automatically to web pages. A list is available at http://www.weatherstations.co.uk/links.htm. The quality of data from most of these is very difficult to assess. Nevertheless, they form a potentially valuable resource for many applications in which spatial and temporal information is important. Most sites have archive data available, so that information from the past few years can be accessed.

The Weather Underground website (www.wunderground.com) gives weather forecasts for locations all over the world, based on national meteorological service information, but also has links to many privately operated weather stations near those places.

Links to sites operated by professional users can be found at http://www.ecn.ac.uk/online_aws/info/location_map.htm.

The availability of data from spatially distributed networks is likely to result in a move away from considering weather at a single point towards the evolution of weather patterns over large areas.

Measurement of Atmospheric Fluxes

Monitoring of near-surface atmospheric conditions with a weather station is important, but tells us little about how those conditions arose. An important control on those conditions is the flux of energy and a wide range of substances in the atmosphere. These include:

- **Water vapour**. An important use of automatic weather stations in hydrology is to determine potential evaporation – that is the amount of evaporation which would occur from a standard crop (usually short grass) if there is no restriction in water supply. Very often such conditions do not exist and actual evaporation is often very different from (usually less than) the potential. The flux of water vapour from the land surface into the lower atmosphere is the evaporation rate and its measurement is of vital importance to hydrologists, plant physiologists and agronomists.
- **Carbon dioxide and methane**. The two most important greenhouse gases. Quantifying, understanding and controlling the release and absorption of these gases is vital in ameliorating climate change.
- **Gaseous pollutants**. A wide range of organic and inorganic gaseous pollutants are released into the atmosphere.
- **Particulates**. These include soot and smoke particles, dust, finely divided chemicals and biological agents, such as bacteria, viruses and pollen.

Methods for monitoring the flux of these substances are needed for environmental and public health purposes.

Two techniques are commonly used for measurement of the exchange of substances between the ground surface and the lower atmosphere. These are known as the Bowen ratio technique and eddy correlation. The Bowen ratio method relies on an assumption that the flux of an atmospheric constituent is related to that of any other through its potential (temperature or concentration) gradient. Thus knowledge of the flux of one substance allows that of any other to be calculated. For the special case of water evaporation (including transpiration), consideration of the energy balance allows the sum of sensible (convected) heat and water vapour flux to be calculated, whilst the Bowen ratio gives their ratio, thus allowing each to be determined.

Eddy correlation has gained in popularity in recent years. The dominant mechanism for transport in the lower atmosphere is turbulent transfer. The instantaneous flux of any substance (including sensible heat and momentum) is then given by the product of its concentration and the vertical air velocity. By integrating this flux over periods of several minutes, an average vertical flux is obtained. The method requires moderately fast response (ideally better than 10 Hz) wind and concentration sensors, although slower sensors can be used by making assumptions about the frequency structure of the variations in concentration. Modern sonic anemometers and infra-red gas analysers are capable of this performance.

Two forms of eddy correlation equipment are in common use. In one, the gas is pumped from the vicinity of the anemometer to a separate gas analyser, similar to a laboratory model, up to about 5 m away. This is known as a closed path system. In an open path system, the gas analyser is constructed so as to allow the air to flow directly through the light path of the analyser, which is mounted adjacent to the anemometer.

Hydra Mark 4

CEH has recently developed a dual gas (water vapour and carbon dioxide) open path eddy correlation system, the Hydra Mark 4, which integrates the gas analyser into a three-dimensional sonic anemometer, eliminating obstruction of the air flow by a separate gas analyser, whilst measuring the gas concentration in the same volume as that of the air movement. At the same time, the single unit is easier to install and use than having two separate items mounted adjacent to one another. The system comes with one logger / processing unit, rather than two or even three, and power requirements are reduced drastically – an important consideration when operating in remote areas. Twelve units have been built for CEH by OSIL of Petersfield, Surrey, UK.

A Hydra Mark 4 integrated open-path, dual gas eddy correlation system monitoring water vapour and carbon dioxide flux on the Berkshire Downs