

Observational Techniques In Situ

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Introduction

We usually refer to *in situ* measurements as those made from some platform anchored to the surface, or in the case of the deep ocean from a ship or buoy. Instruments located on the surface but sensing the atmospheric boundary layer (ABL) remotely are not included. Over land the ABL reaches a height of between 1 and 3 km during the day, collapsing to a few hundred meters at night; the marine boundary layer is typically 500 to 1000 m day and night. The region sampled by *in situ* techniques is mainly in the atmospheric surface layer (ASL). This corresponds roughly to the lowest 10% of the ABL, and its characteristics are influenced strongly by the nature of the surface.

In situ measurements provide data for operational weather forecasting, environmental monitoring, validation for models and remotely sensed observations, and various research topics. The latter include studies of atmospheric structure and transport processes, agricultural and forest meteorology, pollution and climate change. Most applications require measurements of the state variables (temperature, humidity, and pressure), wind speed and direction, incoming and outgoing radiant energy, rainfall, and evaporation. Determination of the fluxes of sensible and latent heat, and of momentum, is also a critical objective of many *in situ* measurement programs.

This article first outlines the theoretical framework of the ASL, which often influences the observations required, and then the sensors commonly used to make the measurements. This is followed by descriptions of a few different types of field site and some practical aspects of deploying instruments and recording the data.

The Atmospheric Surface Layer

To set atmospheric transfer processes within a framework of classical fluid mechanics and thermodynamics, the starting point has been a flat and uniform earth's surface. Many experiments have taken place over such 'ideal' or one-dimensional sites. This article provides a brief and necessarily simplified account of the results, to introduce the quantities whose meas-

urement is considered here. Full details can be found in the works listed under Further Reading.

The defining characteristics of the ASL are its buoyant stability, the vertical variation (or 'profiles') of wind speed, temperature, humidity, and the related vertical fluxes. The latter (so-called eddy fluxes) are given by

$$\tau = -\rho \overline{w'u'} \quad (\text{the flux of momentum, or surface stress}), \quad [1a]$$

$$H = \rho C_p \overline{w'\theta'} \quad (\text{the flux of sensible heat}), \quad \text{and} \quad [1b]$$

$$E = \rho \overline{w'q'} \quad (\text{the flux of latent heat, or evaporation}) \quad [1c]$$

ρ and C_p are density and isobaric specific heat of air, w' , u' , θ' and q' are fluctuations from the mean of vertical and horizontal wind, and of temperature and specific humidity. The overbar indicates a time average of the particular product. Within the ASL over a uniform surface, the fluxes may be assumed constant with height.

The most common measure of thermal stability is based on the relative importance of mechanical and buoyant forces in production of turbulence kinetic energy (TKE); i.e. some function of the ratio of eqn [1a] divided by eqn [1b]. Defining a scaling velocity $u_* = (\tau/\rho)^{1/2}$ and a buoyancy parameter g/T , where g is gravity and T absolute temperature, these form a length scale $L = -u_*^3/[\kappa(g/T)w'\theta']$; κ is a constant (≈ 0.4). The Monin–Obhukov similarity theory (MOST) adopts the hypothesis that, at height z in the boundary layer, flux–gradient relationships and turbulence parameters are universal functions of z/L . These MOST assumptions have been verified by many field experiments.

Wind increases with height in the surface layer while temperature decreases during daytime and increases at night (the nocturnal inversion) in response to the sign of the surface heat flux. MOST has nondimensional forms for the vertical wind and temperature gradients:

$$\phi_m = \frac{\kappa z}{u_*} \frac{\partial \bar{u}}{\partial z} \quad \text{and} \quad \phi_h = \frac{\kappa z}{\theta_*} \frac{\partial \bar{\theta}}{\partial z} \quad [2]$$

respectively, where ϕ_m and ϕ_h are functions of z/L , and $\theta_* = w'\theta'/u_*$ is a scaling temperature. As an example, the variation of wind speed with height is given by integrating the first of these gradient

equations, to obtain

$$\bar{u}(z) = (u_*/\kappa)[\ln(z/z_0) - \psi_m] \quad [3]$$

The integration constant, z_0 , is known as the surface roughness length, and ψ_m is a stability function. It follows that the wind variation with height is roughly logarithmic (exactly so in neutral conditions), and this is also true of the scalar quantities, $\bar{\theta}$ and \bar{q} . Finally, we note that the relationship between fluxes and gradients can be expressed in terms of a turbulent diffusivity,

$$F_\chi = -K_\chi \frac{\partial \chi}{\partial z} \quad [4]$$

where F_χ is the flux of constituent χ (momentum, heat, or a trace gas) and K_χ is its turbulent exchange coefficient, obviously a function of z/L .

Atmospheric Sensors

General Characteristics

There are often several choices of sensor for each variable, the most suitable for a particular application depending on several factors, including the accuracy and resolution required, frequency response, and overall convenience of operation. Sensors evolve continuously in the research environment, either testing new physical principles of measurement or else to quantify some newly significant entity (e.g., a 'greenhouse' gas).

Considerations of frequency response highlight two categories of sensor, which we may call slow and fast. Atmospheric variables fluctuate on time scales from below 0.1 s to several hours. Time-averaging (over 15–30 min) is often required to reduce unsteadiness, so slow-response sensors are adequate to determine basic mean variables, such as \bar{u} , \bar{q} , or $\bar{\theta}$, and their vertical profiles. A sensor responds to a step change exponentially, the time taken to reach $(1 - 1/e; \sim 0.632)$ of the final value being its time response. A slow sensor may have a time response of many seconds. Fast sensors are required when the turbulent fluctuations themselves are of interest, either for studies of atmospheric structure or to determine the surface fluxes by measuring w' , u' , θ' , q' in eqn [1]. For this, frequency response of at least 10 Hz is needed.

The following sections describe first the most common slow-response sensors for atmospheric variables, and then some fast-response instruments. **Figure 1** shows an array of instruments mounted at the top of a 30 m tower, part of the Ozflux network (see below). Sensors described in the text are identified by their letter.

Temperature

Atmospheric temperature can be measured with mercury-in-glass thermometers (still used operationally by weather observers), platinum resistance thermometers (PRTs), thermistors, and thermocouples. The last three lend themselves to automatic data logging. PRTs are very stable, and with careful calibration can achieve an accuracy of about 0.01°C. Thermocouple systems have low output voltage, and for absolute measurement require a reference 'cold' junction. Thermistors are semiconductor devices with higher sensitivity to temperature changes than either of the above, but at the expense of nonlinearity and greater self-heating than platinum elements. Formerly, they were prone to uncertainties of stability and calibration, but interchangeability of $\pm 0.1^\circ\text{C}$ is now possible.

Both thermocouples and PRTs can be easily configured for differential measurement, which can improve accuracy when measuring profiles or the wet-bulb depression of a psychrometer (see the next section). To reduce errors from solar radiation, these thermometers are ideally mounted inside a double-wall heat-reflecting shield and have ambient air drawn over them (A in **Figure 1**).

Humidity

Atmospheric humidity is variously specified by the partial pressure of water vapor (e , in hPa), vapor density (g m^{-3}), specific humidity (q , g/g of moist air), or relative humidity ($\text{RH} = 100e/e_s$). The relationship between them can be found in standard texts. e_s is the liquid water saturation vapor pressure at air temperature, given approximately by the empirical equation

$$e_s = 6.106 \{ \exp [17.273T/(T + 237.3)] \} \quad [5]$$

where T is Celsius temperature. At a particular ambient humidity, reducing air temperature reaches a point on the $T - e_s$ curve (eqn [5]) where the air is saturated. This gives us the principle of the dew point hygrometer. Its central component is a mirror maintained, by optical and electronic feedback, at the temperature where moisture or ice just condense on its surface. It is often considered an absolute instrument, and used as a secondary standard to other sensors.

The traditional instrument for atmospheric humidity measurement is the psychrometer, consisting of a pair of thermometers, one being covered with a moist wick. Air drawn over the thermometers evaporates the moisture, cooling the wick until the evaporation rate is in equilibrium with the vapor content of the air. For given humidity this wet-bulb depression, $(T - T_w)$, is known from thermodynamic theory, leading to the psychrometer equation. The form specified by the World Meteorological Organization (WMO) for

the Assman psychrometer (a particular design of instrument with mercury-in-glass thermometers) is

$$e = e_s - 0.000653 \times (1 + 0.000944T_w)(T - T_w)P \quad [6]$$

where e , e_s , and atmospheric pressure, P , are in the same units. With PRTs in a differential bridge, $\pm 0.01^\circ\text{C}$ is possible for $(T - T_w)$. It is crucial to provide adequate airflow over the thermometers to ensure full depression. With care, accuracy of 0.05 g kg^{-1} is possible. For Assman psychrometers, 0.20 g kg^{-1} is more realistic.

Thin-film polymers which absorb or desorb water as the relative humidity changes afford a simpler humidity sensor. The polymer forms the dielectric of a capacitance in a circuit which provides an output proportional to relative humidity. Early instruments often failed at very high humidity, but recent developments have overcome this problem and have greatly improved their accuracy and stability. Conversion to mixing ratio, specific or absolute humidity requires the air temperature around the dielectric, usually measured with a colocated PRT. These temperature/RH sensors are screened and ventilated in the same way as a psychrometer. The best accuracy quoted is around $\pm 0.3\%$ RH (or $\pm 0.05 \text{ g kg}^{-1}$ at 20°C and 70% RH).

Wind Speed and Direction

For average wind speed and/or direction over some time period, cup (or propeller) anemometers and wind vanes are usually the most convenient. Operational designs must withstand continuous exposure to

stormy conditions, but there are also ‘sensitive’ instruments intended for research work. Apart from mechanical strength, the difference is reflected in their starting speed and distance constant (response time converted to run of wind). A sensitive cup anemometer will start from rest in a breeze of 0.3 m s^{-1} and have a distance constant less than 1 m.

For best accuracy (typically 1%) cups must be calibrated individually, although calibration in the steady horizontal flow of a wind tunnel can lead to uncertainty. In a gusty wind, cup anemometers overestimate for two reasons: the rotor responds more quickly to an increasing wind than to the reverse, and, in a wind gust with a vertical component, shielding by the upwind cup is reduced. A propeller has poor ‘cosine’ response (to off-axis wind direction), but the error is usually minimized by mounting it on the front of a wind vane. A cup-anemometer–wind-vane pair are often mounted at opposite ends of a horizontal bar (B and C in Figure 1).

Pressure

A knowledge of mean atmospheric pressure in the ASL is often needed, in eqn [6] for example, to calculate air density in eqn [1], and to convert between the various definitions of humidity. Pressure varies with elevation above sea level and slowly with synoptic changes. For most purposes, the pressure reported at 3-hourly intervals by the nearest weather forecast station is adequate. The WMO target accuracy for pressure measurement is $\pm 0.1 \text{ hPa}$. It is read from either the traditional mercury column barometer or an accurate aneroid instrument.



Figure 1 An array of meteorological research instruments at the top of a 30 m tower, part of the ‘Ozflux’ long-term climate monitoring network in Australia. (Photo: ©Frank Bradley.)

Rainfall

Rainfall, particularly during convective storms, is perhaps the 'patchiest' of all meteorological variables. Single point measurements are generally less relevant than area averaged values, which may be estimated over land with a network of surface rain gauges. At sea this is not feasible, and while spatial rainfall patterns may be obtained by ship-mounted radars these must be calibrated by a surface measurement.

Traditional rain gauges measure the rain falling into a funnel of known area. For automatic recording either a weighing system is used or a tipping bucket rain gauge. In this, the funnel discharges to a pair of buckets in a seesaw arrangement which flips over at every 0.1 mm of rainfall. Another system, often used on ships, has a reservoir which fills to its capacity (about 50 mm of rain), when it siphons automatically and starts filling again. An electronic sensor keeps track of the level of water in the reservoir. All funnel gauges lose catch in strong winds, when the gauge deflects airflow so that raindrops are carried past the funnel. The siphon gauge also misses rain while the instrument is siphoning.

Optical rain gauges (ORGs) measure rainrate by detecting raindrops falling through an optical path. One system measures extinction of a light beam by the raindrops; another measures the intensity of scintillations caused by raindrops passing through the beam from a light-emitting diode. Rainfall amount is obtained by integrating the rainrate. ORGs must be calibrated against a funnel gauge in natural or simulated rainfall.

Disdrometers are primarily intended for the measurement of drop size and drop distribution in rainfall. The most usual is an acoustic device which converts the sound of impact of raindrops hitting the sensor surface into an electrical signal related to the size of the drop. Continuous recording of the size and number of drops provides a time series of rainrate and total rainfall by integration.

The above rain gauges can handle rainrates to around 200 mm h^{-1} . This would be an extreme tropical storm; a heavy rainstorm in midlatitudes might produce instantaneous rainrates of 50 to 100 mm h^{-1} , but more commonly rainrates over land are between 1 and 20 mm h^{-1} . They are generally unsuitable for the measurement of precipitation falling as snow. However, because of its importance in the hydrological cycle in many regions, it is usual to estimate the water equivalent of snowfall, for example by measuring the average depth of fresh snow cover and its density.

Trace Gas Measurement

Measurement of minor constituents of the atmospheric boundary layer is increasingly important for studies of climate change (the 'greenhouse effect'), and monitoring of air quality. Applications include measuring emissions from engine exhausts and refineries, industrial stacks, agricultural emissions, and vegetation to atmosphere CO_2 exchange. Species of interest include CO , CO_2 , HF , N_2O , NO , NO_2 , CH_4 , SO_2 , NO_x , NH_3 , and other hydrocarbons and organic compounds. Accurate determination of both concentrations and fluxes are required, the former for regulatory purposes and the latter for studies of the emission process.

Chemical analysis and gas chromatography were some of the earliest techniques used, but are not convenient for automatic recording. Infrared gas analyzers (IRGAs) have also been used for absolute measurement of CO_2 and some other atmospheric trace gases. The IRGA measures differential infrared absorption between a pair of cells containing the air sample and a reference gas (or between separate air samples for gradient determination). Originally intended as bench instruments, they are sensitive to vibration and in the field must be installed in a shelter with air samples drawn in through tubes.

Spectrographic methods have also been introduced, the most common being Fourier transform infrared spectroscopy (FTIR). Essentially, the instrument is a scanning interferometer which measures infrared spectra at high resolution over a broad spectral range, measuring all frequencies in the signal simultaneously, and resolving those required with the Fourier transform. Also developed as a laboratory technique, it has been adapted for field use, able to monitor species at very low concentrations (parts per billion of volume). Two configurations are employed: either an open atmospheric path is used, often folded to lengths up to 1 km, or the air is drawn through tubes to an internal measurement cell. Advantages of the open path are that it is noninvasive and that it affords spatial averaging. The internal system permits better temperature and pressure control, and reference to calibration spectra.

Trace gas profiles can be obtained by drawing air continuously from several levels through separate tubes, switched with valves sequentially through either the IRGA or FTIR. With the gradient of a particular constituent determined this way, its flux can be inferred from eqn [4], estimating the exchange coefficient from flux and gradient measurements of some easier quantity (e.g. sensible heat).

Fast-Response Instruments

Fast-response instruments are needed for studies of the turbulent structure of the boundary layer, and for eddy flux measurement. For the wind components, heated wire or film sensors have been used in the field, but poor stability limits their accuracy. Nowadays the usual sensor for turbulent wind measurement is the sonic anemometer (sonic for short), which obtains the wind component, V , along a fixed path length, d , by measuring the transit time of acoustic signals traveling in opposite directions (D in Figure 1). Then $V = c^2(t_2 - t_1)/2d$, where c is the velocity of sound in air. The earliest sonics determined this time difference directly or by measuring phase shift, but had the weakness that c^2 depends on temperature and humidity. Most instruments now use an alternative expression, $V = d(1/t_1 - 1/t_2)/2$. Different designs use various arrangements of the three paths needed to determine the total wind vector. Frequency response depends on the size of the sensing volume, a compromise between the conflicting needs for compactness and minimal flow distortion; d is typically 10–20 cm.

An internal microprocessor determines t_1 and t_2 for each path, and outputs wind components on orthogonal axes. Separate determination of t_1 and t_2 also enables fluctuations in virtual temperature to be obtained from the speed of sound. Then momentum and heat fluxes are calculated with eqns [1a] and [1b]. Temperature fluctuations can also be measured independently with a fine wire, usually of platinum, mounted in the yoke of the sonic; however, it is vulnerable to damage from rain and wind-blown debris.

Measurement of humidity fluctuations are usually based on absorption of either infrared (IR) or ultraviolet (UV) radiation by water vapor. IR instruments usually have a broadband source separated from a detector by an open path of physical length similar to that of the sonic vertical path. A rapidly rotating chopper wheel alternately introduces a pair of narrow-pass interference filters into the beam, one at a strong H₂O absorption line (e.g. 2.61 μm) and the other at a nearby wavelength (e.g. 3.69 μm) of negligible absorption. This ‘differential’ scheme helps compensate for instabilities in the system, such as variations in source intensity. Some IR instruments add another filter at a CO₂ absorption line (e.g. 4.22 μm), to obtain both fluxes simultaneously (E in Figure 1).

The UV instruments detect absorption at the Lyman- α emission line of atomic hydrogen (121.56 nm) or from krypton (116.49 and 123.58 nm). These lines are strongly absorbed, providing good signals with a separation of only 1 cm between the source and the detector. Both types have long-term stability problems, but these are not serious for the

measurement of fluctuations over periods like 15–30 minutes. Neither instrument is normally used for absolute measurement. The humidity sensor must be mounted as close as practicable to the sonic without increasing flow distortion. Formulae are available to correct for loss of correlation by lateral separation of the two instruments.

Fluctuations of static pressure are of interest in turbulence studies, where correlations like $\overline{w'p'}$ represent the transport of TKE by pressure fluctuations. p' is difficult to measure because any probe inserted in the flow may produce dynamic pressure fluctuations which mask those of static pressure. Instruments for this measurement remain research prototypes.

In principle, if a suitable infrared absorption line and fast-response sensor can be found, trace gas fluxes can be measured by the eddy flux method. Some IRGAs respond rapidly enough to measure eddy fluxes, with allowance for the time lag and frequency damping introduced in the air lines. When measuring trace gases, CO₂ and to some extent H₂O by eddy flux, account must be taken of fluctuations of density due to the presence of heat fluxes (the so-called ‘Webb effect’). The corrections can be of the same order as the measured flux.

Radiation Sensors

General

The radiant energy flux to and from the earth’s surface comprises the solar (or short-wave) component in the wavelength band 0.3 to 3 μm , and the terrestrial (long-wave or infrared) component from 3 to around 50 μm . They are measured with a pyranometer and a pyrgeometer respectively. These instruments are physically similar, both accepting broadband radiation through a hemispherical dome of appropriate spectral transmissivity.

Radiation observations can be conveniently discussed in the context of the balance of heat energy at the surface over flat terrain. If R_S and R_L are downwelling short-wave and long-wave radiative energy (W m^{-2}), T_S (K) is surface temperature, G_S is heat flux into the surface, and H and λE the turbulent fluxes,

$$(1 - \alpha)R_S + \varepsilon(R_L - \sigma T_S^4) - G_S = H + \lambda E \quad [7]$$

where α and ε are surface albedo and emissivity, σ the Stefan-Boltzman constant, and λ the latent heat of vaporization.

Short-wave Radiation

Downwelling short-wave radiation at the surface has a component due to the direct solar beam, and a diffuse component scattered from atmospheric constituents

and reflected from clouds. Upwelling short-wave radiation comes from reflection at the surface. Both can be measured with the pyranometer, facing either upward or downward (F and G in Figure 1); their ratio is the surface albedo. The pyranometer sensor is a blackened horizontal surface on which the radiation falls, bonded to a thermopile whose reference junction is the instrument body. Accuracy for the instrument is usually quoted as 2%. The direct solar beam can be measured with a pyrreheliometer. These are more accurate, but are generally unsuitable for operational use because they need to track the sun. Their main use is as calibration standards for working instruments.

The diffuse component is obtained with a 'shadow-band', set to shield the sensor from the direct solar beam. The position of the band is changed manually to follow the annual variation of solar elevation. Instruments have also been built with a rotating shadow band which alternately shields and exposes a fast-response radiation sensor, such as a solid state photocell. This system is less accurate, but useful on ships or other moving platforms.

Long-wave Radiation

Pyrgeometers work by determining the thermal balance of the instrument itself. So as well as the thermopile output, the case and dome temperatures (T_C and T_D) have also to be measured. The long-wave energy passing through the dome is then derived from the pyrgeometer equation

$$R_L = V/s + \sigma T_C^4 + B\sigma(T_C^4 - T_D^4) \quad [8]$$

where V is thermopile output, s its sensitivity, and B an empirically determined constant (~ 3.5). Precision of the instrument using this equation is about 1.5% of the total long-wave flux. The third term on the right represents the effect of dome heating, and the second is the radiative flux contribution from the case of the instrument. The latter is usually the largest term, and is sometimes simulated with an internally generated voltage so that only one signal has to be recorded, instead of three. This, and the necessary assumption that $T_C = T_D$, increases uncertainties to at least 5%.

Net Radiation

Often the net radiant energy (all wavelengths) into or out of the earth's surface is required. This is the algebraic sum of the first two terms of eqn [7]. It can be measured using two pyranometers and two pyrgeometers, or more simply with a net radiometer. This consists of a pair of blackened plates, bonded to the opposite junctions of a thermopile to form a sensor about 25 mm square and 6 mm thick. It is protected by a pair of thin polythene domes, transparent to both

short and long wavelengths, kept inflated with a flow of dry air. The symmetrical arrangement is mounted with the sensor horizontal, measuring the temperature difference produced between the plates by downwelling and upwelling radiative energy (H in Figure 1). The quoted 5% accuracy is poorer than each of the individual instruments, but usually better than their combined uncertainties.

Surface Heat Flux

In eqn [7], G_s is roughly 10% of the net radiation over land and should not be ignored. It is usually measured with a soil heat flux plate, an encapsulated thermopile similar to the net radiometer sensor, buried horizontally at a shallow depth. Heat flux through the plate, assumed to be related to that in adjacent soil, generates a temperature difference between the opposite faces.

Absorption of heat into a water body is more complicated, because incoming short-wave radiation is distributed in depth with an extinction coefficient which depends on turbidity and wavelength. It can penetrate tens of meters into clear water. Incoming long-wave is absorbed within the top millimeter or so. Equation [7] may require additional terms for horizontal and vertical transport of heat (advection) by motion in the water.

Surface Temperature

The surface temperature, T_S , is usually measured with a narrow field of view IR radiometer in the 8–12 μm band. In daytime over land surfaces, T_S will normally vary over quite small distances because of variations in surface cover and topography. Thus, except where the surface is flat and uniform (e.g. bare soil, mown grass) a radiometer measurement from a height of even tens of meters will not be representative of the region. Radiometric measurements of sea surface temperature are more successful, because of the uniformity produced by mixing, and are particularly valuable for the validation of radiometers flown on satellites and aircraft. Corrections must be made for reflected sky radiation, measured with a second radiometer facing skywards, and the emissivity of the water at the particular IR wavelength must be known.

Types of Field Site

General

The physical nature of an experimental site, as well as the purpose of the observations, has a bearing on the instruments and methodology adopted. This section presents some characteristics of various field sites, and the consequences for useful measurement. We envisage midlatitude conditions; the same basic sensors and

procedures are used in tropical and polar regions, perhaps modified to suit the extreme conditions encountered.

Flat, Uniform Landscape

As mentioned above, a theoretical framework for the one-dimensional ASL was derived from measurements at 'ideal' sites. These were located in vast regions with little topographic relief (Australian plains, the US Midwest, the Russian steppe), and the actual observing site was a substantial area of completely uniform surface with short vegetation. Upwind changes in vegetation or soil moisture were avoided. A rule of thumb states that surface uniformity should extend upwind at least 100 times the height of measurement, with no trees or obstacles for many kilometers. Field campaigns in the 1960s rarely used towers higher than about 30 m, so the required fetch was of order 3 km. If application of the results from these experiments to another site is to be strictly valid, it should conform to the same criteria. In practice, useful results may be obtained from less favorable sites, provided the investigator is aware of the implications, and takes appropriate measures. For example, at the field site shown in Figure 2, wind blowing towards the camera would have both profiles and turbulence strongly perturbed by the belt of trees in the background. However the fetch to the left of the picture was clear for some kilometers, so data from that direction were acceptable. The sensor supports face that way and the equipment shelter is located well downwind of the towers.

Plant Canopies and Forests

Some of the earliest studies of the atmospheric surface layer were associated with agriculture and the relationship between climate and plants. Over short ground cover like pasture, the origin of profiles is the surface itself. For tall crops such as corn, orchards and forests, the concept of a zero displacement height, d , evolved, being the level near the top of the plant canopy where the neutral logarithmic wind profile has its origin. In eqn [3], the height z must be replaced by $z - d$. The value of d depends on the structure of the crop, but is usually about $\frac{3}{4}$ of its height.

Within the canopy, branches and leaves are sources and sinks for momentum, heat, moisture and CO_2 , which govern the turbulent exchange processes. To obtain representative profiles of vertical fluxes and concentrations inside the canopy, measurements must be averaged in space as well as time. Canopy profiles merge with the boundary layer profiles near the top of the crop.

Sensors of the same type are used within the canopy as above, but are often smaller. Because of the three-dimensional wind environment, sonic anemometers are preferred over cups. Solar radiation penetrates the canopy and is absorbed and scattered at plant surfaces. Spatially averaged radiation profiles are sometimes obtained by moving the instruments along tracks at various levels through the vegetation. A wide range of specialized sensors have been developed for detailed study of canopy processes, energy exchange, water use, CO_2 uptake, and stomatal conductance, down to the scale of individual leaves.

Non-Uniform Terrain

In the real world, the obstacles and surface nonuniformity so carefully avoided around 'ideal' sites are the normal condition, stimulating efforts to establish general rules to describe such complex terrain. Models have been developed for the two-dimensional internal boundary layers which grow downstream from a change in surface, and a sequence of such changes like the checkerboard pattern of agricultural land. There has also been some success in modeling wind flow over one- and two-dimensional hills.

Over such topography, observational problems escalate. A uniform site can be represented by a single vertical profile of instruments. To document the boundary layer over complex terrain requires many measuring sites and more sets of instruments. Their number, height and location depends on the particular aims of the study, and must be to some extent intuitive. For example, is it enough to sample the extremes of the site (a hilltop and a valley), or must we also investigate sites in between?

Some guidance may be gained from simple modeling of the flow field. This, and the analysis of data from hilly sites, is often performed in a coordinate framework based on the streamlines of the flow. At any point in this curvilinear system, the x axis is along the local mean velocity vector, with the other two axes normal to it and to one another.

As the physical scale of topography increases, surface influence propagates higher into the ABL, beyond the range which can be studied exclusively with *in situ* techniques. This is where the combined strengths of *in situ*, remote sensing, and aircraft operations become important.

The Ocean

The ocean surface is notably horizontal, uniform and homogeneous. One-dimensional assumptions, turbulence theory, and the MOST relationships apply to the marine boundary layer. However, exchange between ocean and the atmosphere involves additional physical



Figure 2 A micrometeorological research site in south-eastern Australia, set up by CSIRO Land and Water. The towers carry instruments to measure the profiles of wind, temperature, and humidity, the components of radiation, and eddy fluxes of heat, moisture and CO_2 , as part of a regional climate study. The tallest tower is 22 metres high; a shelter for recording equipment is seen to the right of the picture. (Photo: ©Greg Heath.)

processes associated with the waves, surface currents, and heat transfer in the water.

Most of the sensors described above are used at sea, but designed to survive the more hostile conditions. Wind, temperature, and rainfall measurements can be impaired by the presence of the ship. When practical, meteorological sensors are mounted on a jackstaff at the bow, in relatively clear air and ahead of spray from the ship's bow wave, or high on the mainmast with instruments duplicated on port and starboard sides. Psychrometers are seldom used because of the frequent need to wash salt from the wick. More usually, temperature and humidity are measured with the thin-film polymer package. Radiation instruments are mounted as high as possible, preferably in gimbals. The domes require daily washing to remove salt and particulates from the ship's exhaust. Upwelling radiation components are calculated from sea surface temperature, emissivity, and albedo.

Eddy fluxes are measured with the usual fast-response instruments, the sonic wind signals being corrected for ship motion measured with an inertial navigation system (INS), containing accelerometers, rate sensors, gyros, etc. The inertial dissipation technique of flux measurement (see Further Reading) is also used at sea, being less affected by flow distortion and ship motion. This also requires the fluctuations w' , u' , θ' , q' , but within the inertial subrange.

Over the ocean, a finite difference form of eqn [4], $F_\chi = C_\chi(\chi_S - \chi_A)$, is commonly used for flux calcula-

tion. C_χ is the exchange coefficient for variable χ and subscripts S and A refer to values at the surface and a reference height (usually 10 m). Values of C_χ have progressed from constants or simple functions of wind speed, to sophisticated forms embodying flux-gradient stability relationships and effects of sea state. These require iterative computer codes which calculate momentum, sensible and latent heat fluxes simultaneously (so-called bulk flux algorithms). Radiometric measurement of sea surface temperature is preferred, because skin temperature is the physically correct value to use for air-sea exchange. However, sufficiently accurate IR radiometers are seldom available, so T_S is measured at some depth below the surface. Some flux algorithms take account of the difference between this (bulk) value and skin temperature.

Long-term Observation Sites

Any description of *in situ* methods would be incomplete without reference to surface observations made worldwide by national weather services. Their principal purpose is for weather, aviation, and shipping forecasts, and increasingly for climatology, but they also provide data for community use. The variables recorded, and often the sensors used, are the same as those needed for research. Research experiments tend to record continuous time series at high resolution over relatively limited periods. Weather observations

feature discrete data sampling (1–3 h, depending on the station), but on a regular and continuing basis.

The value of this data is enhanced by the careful documentation and quality control performed by the forecasting services, and the fact that instruments, sites and observational procedures conform to agreed international practice. Meteorological services do not adopt new instrument types without international comparisons, and avoid too many changes to preserve homogeneity of the climate record. The requirements for instruments (such as accuracy and calibration) and observation procedures are set out in WMO (1986).

Increasingly, automatic weather stations (AWS) are being developed and installed worldwide, taking advantage of technological advances in sensor development, computer capability, and communications. Data transmission from remote sites is possible by satellite or phone. Other advantages include more frequent sampling, exact timing, and avoidance of human error. This not only improves the forecast, but both the real-time and archived data are a quality resource for research.

A global network of stations has also been established for long-term measurement of land–atmosphere carbon, water, and energy exchange. Known as ‘flux stations’, they are operated by research institutions in various regions: ‘Ameriflux’, ‘Euroflux’, ‘Ozflux’ (Australia), etc. The principal measurement is of the eddy fluxes using the fast-response instruments described above, but a full suite of meteorological instruments is also maintained. Like the AWS, data are transmitted to base by a telemetry link.

Experimental Procedures

Platforms

Over land, instruments are usually mounted on a guyed mast or tower. To avoid distortion of the wind flow, these are as slim as possible without losing rigidity. Sensors are mounted at the end of arms, oriented in the direction of the prevailing wind. To accommodate winds from all directions, sensors are often duplicated on opposite sides of the mast. Equation [3] indicates that the profiles will be best defined with logarithmically spaced sensors.

Up to a few meters in height, the mast can be a simple tube, perhaps only 10 cm diameter. Taller masts are usually the climbable lattice type of triangular cross-section and about 30 cm side. Both types are shown in **Figure 2**, the near lattice tower being 22 m high; the practical limit is about 60 m. Beyond this, a major structure is necessary with a small elevator to transport equipment and personnel to the upper levels. Several such research towers have been built to heights

around 300 m; the best known are by USA/NOAA at Boulder, the Dutch Meteorological Institute at Cabauw, and the Japanese Meteorological Agency at Tsukuba. More elaborate measures must be taken to extend the sensors far enough from these towers to minimize interference.

At shallow water sites, such as lakes and the coastal ocean, masts and research platforms have been built on the seafloor. Over the deep ocean, platforms are either ships or moorings. The difficulties of operating from ships have already been mentioned, particularly distortion of measurements by their bulk. Spar and toroidal buoys moored to the seabed also experience motion, but are less obtrusive. Toroids usually carry a frame for instruments to the height of about 4 m. Networks of such moorings have been installed in climatically important regions, such as the tropical Pacific. They return data daily via satellite and can operate unattended for periods of six-months or longer. The most serious setback to reliability is not technical, but vandalism.

Figure 3 shows a unique and much-used facility called FLIP (FLOating Instrument Platform) developed by the Scripps Institution of Oceanography. In effect a huge spar buoy 300 m long, it is towed on site and the lower part flooded so that it actually flips into the vertical. In this deployment, it is set up to measure the structure of the marine ASL. The photograph highlights the multiple sensors needed to determine variability with height, and the long boom to minimize the influence of the bulky platform.

Combined operation of aircraft with *in situ* platforms has proved highly effective. While surface-mounted instruments perform continuous time sampling, the aircraft complements this with spatial sampling over the surrounding region. Missions are often flown only 30 m above the surface, mostly using the sensors described above. **Figure 4** shows an aircraft equipped for boundary layer research; turbulent wind components are measured with pressure probes (C and F in **Figure 4**) corrected for aircraft motion with INS (I), temperature with thermistors or PRTs (A), mean humidity with a dew point hygrometer (B), and humidity fluctuations with Lyman- α or IR sensors (D and G). The latter may also be measured with a refractometer, which detects fluctuations of the radio refractive index of air, which depends on humidity, temperature, and pressure, in a microwave cavity. The advent of miniature electronics and the GPS navigation system has enabled development of miniature autonomous robotic aircraft, which can potentially play a valuable role in boundary layer studies.

Tethered balloons have been used to suspend instruments through the ABL, and may thus provide



Figure 3 The floating instrument platform (FLIP) operated by Scripps Institution of Oceanography, La Jolla, CA, USA. FLIP is shown here set up for an investigation of the marine boundary layer by the Atmospheric Turbulence Laboratory of the University of California at Irvine. The boom is 20 m long and 12 m above the sea surface. It carries a vertical mast with instruments to measure profiles of wind and temperature, atmospheric turbulence and the fluxes of heat, moisture and momentum (Photo: © Carl Friehe.)

an alternative *in situ* platform within the height range of tall (300 m) towers. Their main advantage is portability and rapid deployment; an obvious difficulty is their instability. Instruments are attached to the tether cable at various levels although the actual height of measurement fluctuates with balloon motion. Eddy-flux measurements have been made from tethered balloons, the attachment for the flux package being designed to maintain its verticality and orientation. A development of this technique is the kytoon, a kite-shaped balloon which provides aerodynamic lift and better stability.

Sampling and Data Recording

When planning a series of observations it is important to consider the sampling required to achieve the aims of the project. We have seen that nonuniform terrain

places demands on spatial sampling. Sampling in time, even in the one-dimensional case, has several aspects. An instantaneous profile will be uneven because of turbulent fluctuations on many scales. Smooth profiles are obtained by averaging ensembles of many profiles over some period, which should be long enough to include most of the low frequency eddies, but avoid diurnal nonstationarity. In the surface layer, a period of 15–30 minutes is convenient.

This identifies the environmental time constraint to obtain realistic mean values. For sampling rate we consider the time response of the sensor. In the case of a ‘slow’ sensor (e.g. a platinum thermometer) this may be many seconds, much slower than the high-frequency end of the atmospheric spectrum. So the sensor rather than the variable determines the sample time; in practice 2–5 samples within the transducer time constant is sufficient.



Figure 4 A Twin Otter research aircraft operated by the US Department of the Navy, equipped with sensors to study wind, temperature, and humidity structure in the atmospheric boundary layer (Photo: © Carl Friehe.)

Between the energy-containing low-frequency eddies of the atmospheric spectrum, and the high-frequency eddies which dissipate turbulence energy to heat, is a region known as the inertial subrange. This covers the spectral range from about 10 Hz to 0.1 Hz. Thus, to determine turbulence statistics and the eddy fluxes we need not resolve higher frequencies than 10 Hz. According to Shannon's sampling theorem, to reconstruct the original signal without aliasing, this implies a sampling rate of 20 Hz. The fast-response instruments described above for w' , u' , θ' , and q' have been designed accordingly.

Dramatic improvements in computing speed and recording media, and reduced costs have revolutionized data recording practice. In the past it was usual to sample at the highest frequency required but record only average values. Time series of turbulent fluctuations filled racks of computer tapes. Now that data storage is no longer a restriction, all data can be archived at the original sampling speed, to enable reanalysis at some later date. Ready availability of CD-ROM writers makes large data sets secure and portable.

See also

Agricultural Meteorology and Climatology. Air-Sea Interaction: Momentum, Heat and Vapor Fluxes. **Boundary Layers:** Complex Terrain; Surface Layer. **Data Analysis:** Time Series Analysis. **Land-Atmos-**

phere Interactions: Canopy Processes; Trace Gas Exchange. **Observations for Chemistry (Remote Sensing):** Microwave. **Operational Meteorology.**

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