The sensor is thus almost always poorly coupled to the seafloor and sensor resonances can occur within the frequency range of interest for short period sensors. Fortunately, these resonances have little effect on lower frequencies. However, lower frequency sensors are affected, since a soft foundation permits tilt either in response to sediment deformation by the weight of the sensor or in response to water currents. The existing Webb instruments combat this problem by periodic releveling of the sensor gimbals. The PMD sensors have an advantage here in that the mass element is a fluid and the horizontal components self-level to within 5°.

Why not use hydrophones then? These make leveling unnecessary and are more robust mechanically. In terms of sensitivity, they are comparable to seismometers. The disadvantage of hydrophones lies in the physics of reverberation in the water layer. A pulse incident from below is reflected from the sea surface completely, and when it encounters the seafloor it is reflected to a significant degree. Since the seafloor has a higher acoustic impedance than water, the reflected pressure pulse has the same sign as the incident pulse and the signal is large. However, the seafloor motion associated with pressure pulses traveling in opposite directions is opposite in sign, so cancellation occurs. Unfortunately, the frequency range in which these reverberations are troublesome is in the low noise region. **Figures 7** and 8 show synthetic seismograms of pressure and vertical motion illustrating this effect.

See also

Mid-Ocean Ridge Seismic Structure. Seismic Structure.

Further Reading

Barash TW, Doll CG, Collins JA, Sutton GH and Solomon SC (1994) Quantitative evaluation of a passively leveled ocean bottom seismometer. *Marine Geophysical Researches* 16: 347–363.

Dorman LM (1997) Propagation in marine sediments. In: Crocker MJ ed. *Encyclopedia of Acoustics*, pp. 409–416. New York, John Wiley.

Dorman LM, Schreiner AE and Bibee LD (1991) The effects of sediment structure on sea floor noise. In: Hovem J *et al.* (eds) *Proceedings of Conference on Shear Waves in Marine Sediments*, pp. 239–245. Dordrecht: Kluwer Academic Publishers.

Duennebier FK and Sutton GH (1995) Fidelity of ocean bottom seismic observations. *Marine Geophysical Researches* 17: 535–555.

Jacobson RS, Dorman LM, Purdy GM, Schultz A and Solomon S (1991) *Ocean Bottom Seismometer Facilities Available*, EOS, Transactions AGU, 72, pp. 506, 515.

Sauter AW, Hallinan J, Currier R *et al.* (1990) *Proceedings of the MTS Conference on Marine Instrumentation*, pp. 99–104.

Tryon M, Brown K, Dorman L and Sauter A (2001) A new benthic aqueous flux meter for very low to moderate discharge rates. *Deep Sea Research* (in press).

Webb SC (1998) Broadband seismology and noise under the ocean. *Reviews in Geophysics* 36: 105–142.

SENSORS FOR MEAN METEOROLOGY

K. B. Katsaros, Atlantic Oceanographic and Meteorological Laboratory, NOAA, Miami, FL, USA

doi:10.1006/rwos.2001.0329

Introduction

Basic mean meteorological variables include the following: pressure, wind speed and direction, temperature, and humidity. These are measured at all surface stations over land and from ships and buoys at sea. Radiation (broadband solar and infrared) is also often measured, and sea state, swell, wind sea, cloud cover and type, and precipitation and its intensity and type are evaluated by an observer over the ocean. Sea surface temperature and wave height (possibly also frequency and direction of wave trains) may be measured from a buoy at sea; they are part of the set of parameters required for evaluating net surface energy flux and momentum transfer. Instruments for measuring the quantities described here have been limited to the most common and basic. Precipitation is an important meteorological variable that is measured routinely over land with rain gauges, but its direct measurement at sea is difficult because of ship motion and wind deflection by ships' superstructure and consequently it has been measured routinely over the ocean only from ferry boats. However, it can be estimated at sea by satellite techniques, as can surface wind and sea surface temperature. Satellite methods are included in this article, since they are increasing in importance and provide the only means for obtaining complete global coverage.

Pressure

Several types of aneroid barometers are in use. They depend on the compression or expansion of an evacuated metal chamber for the relative change in atmospheric pressure. Such devices must be compensated for the change in expansion coefficient of the metal material of the chamber with temperature, and the device has to be calibrated for absolute values against a classical mercury in glass barometer, whose vertical mercury column balances the weight of the atmospheric column acting on a reservoir of mercury. The principle of the mercury barometer was developed by Evangilista Toricelli in the 17th century, and numerous sophisticated details were worked out over a period of two centuries. With modern manufacturing techniques, the aneroid has become standardized and is the commonly used device, calibrated with transfer standards back to the classical method. The fact that it takes a column of about 760 mm of the heavy liquid metal mercury (13.6 times as dense as water) illustrates the substantial weight of the atmosphere. Corrections for the thermal expansion or contraction of the mercury column must be made, so a thermometer is always attached to the device. Note that the word 'weight' is used, which implies that the value of the earth's gravitational force enters the formula for converting the mercury column's height to a pressure (force/unit area). Since gravity varies with latitude and altitude, mercury barometers must be corrected for the local value of the acceleration due to gravity.

Atmospheric pressure decreases with altitude. The balancing column of mercury decreases or the expansion of the aneroid chamber increases as the column of air above the barometer has less weight at higher elevations. Conversely, pressure sensors can therefore be used to measure or infer altitude, but must be corrected for the variation in the atmospheric surface pressure, which varies by as much as 10% of the mean (even more in case of the central pressure in a hurricane). An aneroid barometer is the transducer in aircraft altimeters.

Wind Speed and Direction

Wind speed is obtained by two basic means, both depending on the force of the wind to make an object rotate. This object comprises either a three- or four-cup anemometer, half-spheres mounted to horizontal axes attached to a vertical shaft (**Figure 1A**). The cups catch the wind and make the shaft rotate. In today's instruments rotations are counted by the frequency of the interception of a light source to produce a digital signal.

Propeller anemometers have three or four blades that are turned by horizontal wind (**Figure 1B**). The propeller anemometer must be mounted on a wind vane that keeps the propeller facing into the wind. For propeller anemometers, the rotating horizontal shaft is inserted into a coil. The motion of the shaft generates an electrical current or a voltage difference that can be measured directly. The signal is large enough that no amplifiers are needed.

Both cup and propeller anemometers, as well as vanes, have a threshold velocity below which they do not turn and measure the wind. For the propeller anemometer, the response of the vane is also crucial, for the propeller does not measure wind speed off-axis very well. These devices are calibrated in wind tunnels, where a standard sensor evaluates the speed in the tunnel. Calibration sensors can be fine cup anemometers or pitot tubes.

The wind direction is obtained from the position of a wind vane (a vertical square, triangle, or otherwise shaped wind-catcher attached to a horizontal shaft, **Figures 1A and B**). The position of a sliding contact along an electrical resistance coil moved by the motion of the shaft gives the wind direction relative to the zero position of the coil. The position is typically a fraction of the full circle (minus a small gap) and must be calibrated with a compass for absolute direction with respect to the Earth's north.

Other devices such as sonic anemometers can determine both speed and direction by measuring the modification of the travel time of short sound pulses between an emitter and a receiver caused by the three-dimensional wind. They often have three sound paths to allow evaluation of the three components of the wind (**Figure 1C**). These devices have recently become rugged enough to be used to measure mean winds routinely, and have a high enough frequency response to also determine the turbulent fluctuations. The obvious advantage is that the instrument has no moving parts. Water on the sound transmitter or receiver causes temporary difficulties, so a sonic anemometer is not an all-weather instrument. The sound paths can be at arbitrary angles to each other and to the natural vertical. Processing of the data transforms the measurements into an Earth-based coordinate system. The assumptions of zero mean vertical velocity and zero mean cross-wind velocity allow the relative orientation between the instrument axes and the Earth-based coordinate system to be found. Difficulties arise if the instrument is experiencing a steady vertical velocity at its location due to flow distortion around the measuring platform, for instance.

Cup and propeller anemometers are relatively insensitive to rain. However, snow and frost are problematic to all wind sensors, particularly the ones described above with moving parts. Salt

Figure 1 (A) Cup anemometer and vane; (B) propeller vane assembly; (C) three-dimensional sonic anemometer; (D) radiation shield for temperature and humidity sensors. (Photographs of these examples of common instruments were provided courtesy of R.M. Young Company.)

contamination over the ocean also causes deterioration of the bearings in cup and propeller anemometers. Proper exposure of wind sensors on ships is problematic because of severe flow distortion by increasingly large ships. One solution has been to have duplicate sensors on port and starboard sides of the ship and selecting the valid one on the basis of the recording of the ship's heading and the relative wind direction.

Temperature

The measurements of both air and water temperature will be considered here, since both are important in air–sea interaction. Two important considerations for measuring temperature are the exposure of the sensor and shielding from solar radiation. The axiom that a 'thermometer measures its own temperature' is a good reminder. For the thermometer to represent the temperature of the air, it must be well ventilated, which is sometimes assured by a protective housing and a fan pulling air past the sensor. Shielding from direct sunlight has been done traditionally over land and island stations by the use of a 'Stephenson screen,' a wooden-roofed box with slats used for the sides, providing ample room for air to enter. Modern devices have individual housings based on the same principles (**Figure 1D**).

The classic measurements of temperature were done with mercury in glass or alcohol in glass thermometers. For sea temperature, such a thermometer was placed in a canvas bucket of water hauled up on deck. Today, electronic systems have replaced most of the glass thermometers. **Table 1** lists some of these sensors (for details see the Further Reading section).

The sea surface temperature (SST) is an important aspect of air–sea interaction. It enters into bulk formulas for estimating sensible heat flux and evaporation. The temperature differences between the air at one height and the SST is also important for determining the atmospheric stratification, which can modify the turbulent fluxes substantially compared with neutral stratification.

The common measure of SST is the temperature within the top 1 or 2 m of the interface, obtained with any of the contact temperature sensors described in **Table 1**. On ships, the sensor is typically placed in the ship's water intake, and on buoys it may even be placed just inside the hull on the bottom, shaded side of the buoy. Because the heat losses to the air occur at the air–sea interface, while solar heating penetrates of the order of tens of meters (depth depending on sun angle), a cool skin, 1–2 mm in depth and 0.1–0.5°C cooler than the lower layers, is often present just below the interface. Radiation thermometers are sometimes used from ships or piers to measure the skin temperature directly (*see* **Radiative Transfer in the Ocean**).

Humidity

The Classical Sling Psychrometer

An ingenious method for evaluating the air's ability to take up water (its deficit in humidity with respect to the saturation value, *see* **Evaporation and Humidity**) is the psychrometric method. Two thermometers (of any kind) are mounted side by side, and one is provided with a cotton covering (a wick) that is wetted with distilled water. The sling psychrometer (**Figure 2**) is vigorously ventilated by swinging it in the air. The air passing over the sensors changes their temperatures to be in equilibrium with the air; the dry bulb measures the actual air temperature, the wet bulb adjusts to a temperature that is intermediate between the dew point and air temperature. As water from the wick is evaporated, it takes heat out of the air passing over the wick until an equilibrium is reached between the heat supplied to the wet bulb by the air and the heat lost due to evaporation

Table 1 Electronic devices for measuring temperature in air or water

Name	*Principle*	*Typical use*
Thermocouple	Thermoelectric junctions between two wires (e.g. Copper-Constantan) set up a voltage in the circuit, if the junctions are at different temperatures. The reference junction temperature must be measured as well	Good for measuring differences of temperature
Resistance thermometer	$R = R_{\mathrm{Ref}}(1 + \alpha T)$ Where R is the electrical resistance, R_{Ref} is resistance at a reference temperature, and α is the temperature coefficient of resistance	Platinum resistance thermometers are used for calibration and as reference thermometers
Thermistor	$R = a \exp(b/T)$ Where R is resistance, T is absolute temperature, and a and b are constants	Commonly used in routine sensor systems
Radiation thermometer	Infrared radiance in the atmospheric window, 8–12 μm, is a measure of the equivalent black body temperature	Usually used for measuring water's skin temperature

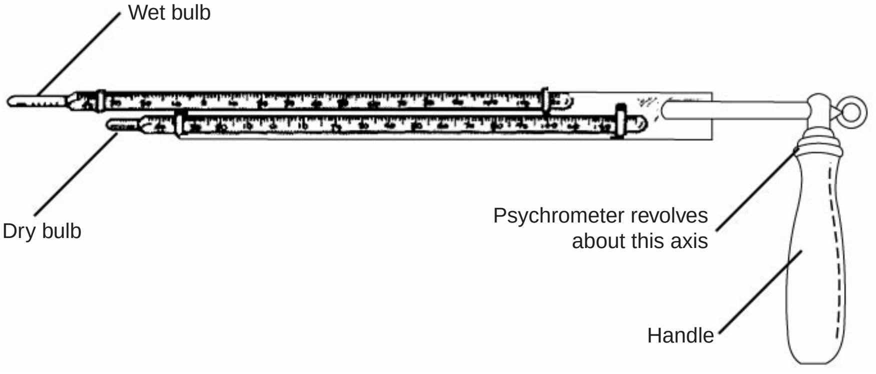

Figure 2 Sling pyschrometer. (Reproduced with permission from Parker, 1977.)

of water from the wick. This is the wet bulb temperature. The *Smithsonian Tables* provide the dew point temperature (and equivalent saturation humidity) corresponding to the measured 'wet bulb temperature depression,' i.e. the temperature difference between the dry bulb and the wet bulb thermometers at the existing air temperature.

Resistance Thermometer Psychrometer

A resistance thermometer psychrometer consists of stainless steel-encased platinum resistance thermometers housed in ventilated cylindrical shields. Ventilation can be simply due to the natural wind (in which case errors at low wind speeds may develop), or be provided by a motor and a fan (typically an air speed of $3\,\mathrm{m\,s^{-1}}$ is required). A water reservoir must be provided to ensure continuous wetting of the wet bulb. The reservoir should be mounted below the psychrometer so that water is drawn onto the wet bulb with a long wick. (This arrangement assures that the water has had time to equilibrate to the wet bulb temperature of the air.)

If these large wet bulbs collect salt on them over time, the relative humidity may be in error. This is not a concern for short-term measurements. A salt solution of 3.6% on the wet bulb would result in an overestimate of the relative humidity of approximately 2%.

Capacitance Sensors of Humidity

The synoptic weather stations often use hygrometers based on the principle of capacitance change as the small transducer absorbs and desorbs water vapor. To avoid contamination of the detector, special filters cover the sensor. Dirty filters (salt or other contaminants) may completely mask the atmospheric effects. Even the oil from the touch of a human hand is detrimental. Two well-known sensors go under the names of Rotronic and Humicap. Calibration with mercury in glass psychrometers is useful.

Exposure to Salt

As for wind and temperature devices, the humidity sensors are sensitive to flow distortion around ships and buoys. Humidity sensors have an additional problem in that salt crystals left behind by evaporating spray droplets, being hygroscopic, can modify the measurements by increasing the local humidity around them. One sophisticated, elegant, and expensive device that has been used at sea without success is the dew point hygrometer. It depends on the cyclical cooling and heating of a mirror. The cooling continues until dew forms, which is detected by changes in reflection of a light source off the mirror, and the temperature at that point is by definition the dew point temperature. The problem with this device is that during the heating cycle sea salt is baked onto the mirror and cannot be removed by cleaning.

Several attempts to build devices that remove the spray have been tried. Regular Stephenson screen-type shields provide protection for some time, the length of which depends both on the generation of spray in the area, the height of the measurement, and the size of the transducer (i.e. the fraction of the surface area that may be contaminated). One of the protective devices that was successfully used in the Humidity Exchange over the Sea (HEXOS) experiment is the so-called 'spray flinger.'

Spray-Removal Device

The University of Washington 'spray flinger' (**Figure 3**) was designed to minimize flow modification on scales important to the eddy correlation calculations of evaporation and sensible heat flux employing

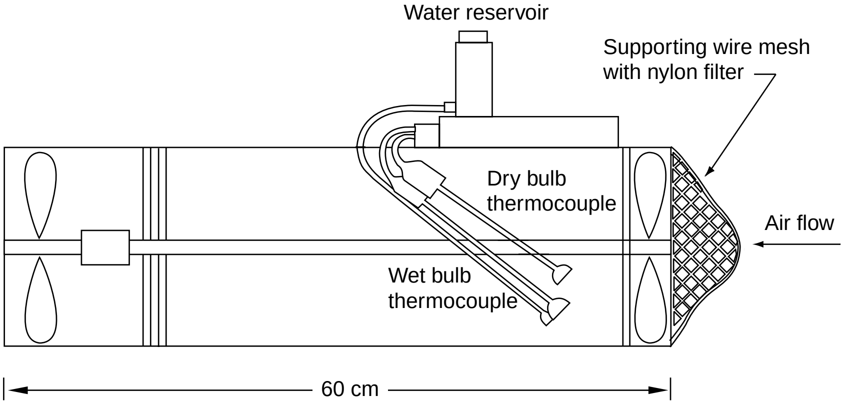

Figure 3 Sketch of aspirated protective housing, the 'spray flinger', used for the protection of a thermocouple psychrometer by the University of Washington group. The system is manually directed upwind. The spray flinger is a 60 cm long tube, 10 cm in diameter, with a rotating filter screen and fan on the upwind end, and an exit fan and the motor at the downwind end. The filter is a single layer of nylon stocking, which is highly nonabsorbent, supported by a wire mesh. Particles and droplets are intercepted by the rotating filter and flung aside, out of the airstream entering the tube. The rotation rate of the filter is about 625 rpm. Inspection of the filter revealed that this rate of rotation prevented build-up of water or salt. The nylon filter needs to be replaced at least at weekly intervals. (Reproduced with permission from Katsaros *et al.*, 1994.)

data from temperature and humidity sensors inside the housing. The design aims to ensure that the droplets removed from the airstream do not remain on the walls of the housing or filter where they could evaporate and affect the measurements. The device has been tested to ensure that there are no thermal effects due to heating of the enclosure, but this would be dependent on the meteorological conditions encountered, principally insolation. The housing should be directed upwind.

Although there is a slow draw of air through the unit by the upwind and exit fans ($1\text{–}2\,\mathrm{m\,s^{-1}}$), it is mainly a passive device with respect to the airflow. Inside the tube, wet and dry thermocouples or other temperature and humidity sensors sample the air for mean and fluctuating temperature and humidity. Wind tunnel and field tests showed the airflow inside the unit to be steady and about one-half the ambient wind speed for wind directions $< 40^\circ$ off the axis. Even in low wind speeds there is adequate ventilation for the wet bulb sensor. Comparison between data from shielded and unshielded thermocouples (respectively, inside and outside the spray flinger) show that the measurements inside are not noticeably affected by the housing.

A quantitative test of the effectiveness of the spray flinger in removing aerosols from the sample airstream was performed during HEXMAX (the HEXOS Main Experiment) using an optical particle counter to measure the aerosol content with diameters between 0.5 and 32 μm in the environmental air and at the rear of the spray flinger. Other devices have been constructed, but have had various difficulties, and the 'spray flinger' is not the final answer. Intake tubes that protect sensors have also been designed for use on aircraft.

Satellite Measurements

With the global ocean covering 70% of the earth's surface, large oceanic areas cannot be sampled by *in situ* sensors. Most of the meteorological measurements are taken by Voluntary Observing Ships (VOS) of the merchant marine and are, therefore, confined to shipping lanes. Research vessels and military ships may be found in other areas and have contributed substantially to our knowledge of conditions in areas not visited by VOS. The VOS report their observations on a 3 hour or 6 hour schedule. Some mean meteorological quantities such as SST and wind speed and direction are observable by satellites directly, while others can be inferred from less directly related measurements. Surface insolation and precipitation depend on more complex algorithms for evaluation. Satellite-derived surface meteorological information over the ocean are mostly derived from polar-orbiting, sun-synchronous satellites. The famous TIROS and NOAA series of satellites carrying the Advanced Very High Resolution Radiometer (AVHRR) and its predecessors has provided sea surface temperature and cloud information for more than three decades (SST only in cloud-free conditions). This long-term record of consistent measurements by visible and infrared sensors has provided great detail with a resolution of a few kilometers of many phenomena such as oceanic eddy formation, equatorial Rossby and Kelvin waves, and the El Niño phenomenon.

Because of the wide swath of these short wavelength devices, of the order of 2000 km, the whole earth is viewed daily by either the ascending or descending pass of the satellite overhead, once in daytime and once at night.

Another mean meteorological variable observable from space is surface wind speed, with microwave radiometers and the wind vector from scatterometers, active microwave instruments. Both passive and active sensors depend on the changing roughness of the sea as a function of wind speed for their ability to 'sense' the wind. The first scatterometer was launched on the Seasat satellite in 1978, operating for 3 months only. The longest record is from the European Remote Sensing (ERS) satellites 1 and 2 beginning in 1991 and continuing to function well in 2000. Development of interpretation of the radar returns in terms of both speed and direction depends on the antennae viewing the same ocean area several times at different incidence angles relative to the wind direction. A recently launched satellite (QuikSCAT in 1999) carries a new design with a wider swath, the SeaWinds instrument. Scatterometers are providing surface wind measurements with accuracy of $\pm\ 1.6\,\mathrm{m\,s^{-1}}$ approximately in speed and $\pm 20^\circ$ in direction at 50 km resolution for ERS and 25 km for SeaWinds. They view all of the global ocean once in 3 days for ERS and in approximately 2 days for QuikSCAT. Microwave radiometers such as the Special Sensor Microwave/Imager (SSM/I), operational since 1987 on satellites in the US Defense Meteorological Satellite Program, have wider swaths covering the globe daily, but they are not able to sense the ocean surface in heavy cloud or rainfall areas and do not give direction. They can be assimilated into numerical models where the models provide an initial guess of the wind fields, which are modified to be consistent with the details of the radiometer-derived wind speeds.

Surface pressure and atmospheric surface air temperature are not yet amenable to satellite observations, but surface humidity can be inferred from total column water content (*see* **Evaporation and Humidity**). From the satellite-observed cloudiness, solar radiation at the surface can be inferred by use of radiative transfer models. This is best done from geostationary satellites whose sensors sweep across the Earth's surface every 3 hours or more often, but only view a circle of useful data extending $\pm 50^\circ$ in latitude, approximately.

Precipitation can also be inferred from satellites combining microwave data (from SSM/I) with visible and infrared signals. For tropical regions, the Tropical Rainfall Measuring Mission (TRMM) on a low-orbit satellite provides precipitation estimates on a monthly basis. This satellite carries a rain radar with 500 km swath in addition to a microwave radiometer.

Developments of multispectral sensors and continued work on algorithms promises to improve the accuracy of the satellite information on air–sea interaction variables. Most satellite programs depend on the simple *in situ* mean meteorological measurements described above for calibration and validation. A good example is the important SST record provided by the US National Weather Service and used by all weather services. The analysis procedure employs surface data on SST from buoys, particularly small, inexpensive, free-drifting buoys that are spread over the global oceans to 'tie-down' the correction for atmospheric interference for the satellite estimates of SST. The satellite-observed infrared radiances are modified by the transmission path from the sea to the satellite, where the unknown is the aerosol that can severely affect the interpretation. The aerosol signal is not directly observable yet by satellite, so the surface-measured SST data serve an important calibration function.

Future Developments

New measurement programs are being developed by international groups to support synoptic definition of the ocean's state similarly to meteorological measurements and to provide forecasts. The program goes under the name of the Global Ocean Observing System (GOOS). It includes new autonomous buoys cycling in the vertical to provide details below the interface, a large surface drifter component, and the VOS program, as well as certain satellite sensors. The GOOS is being developed to support a modeling effort, the Global Ocean Data Assimilation Experiment (GODAE), which is an experiment in forecasting the oceanic circulation using numerical models with assimilation of the GOOS data.

See also

Evaporation and Humidity. Heat and Momentum Fluxes at the Sea Surface. Sensors for Micrometeorological Flux Measurements. Wind Driven Circulation.

Further Reading

Atlas RS, Hoffman RN, Bloom SC, Jusem JC and Ardizzone J (1996) A multiyear global surface wind velocity data set using SSM/I wind observations. *Bulletin of the American Meteorological Society* 77: 869–882.

Bentamy A, Queffeulou P, Quilfen Y and Katsaros KB (1999) Ocean surface wind fields estimated from satellite active and passive microwave instruments. *IEEE Transactions Geosci Remote Sens.* 37: 2469–2486.

de Leeuw G (1990) Profiling of aerosol concentrations, particle size distributions, and relative humidity in the atmospheric surface layer over the North Sea. *Tellus* 42B: 342–354.

Dobson F, Hasse L and Davies R (eds) (1980) *Instruments and Methods in Air–Sea Interaction*, pp. 293–317. New York: Plenum.

Geernaert GL and Plant WJ (eds) (1990) *Surface Waves and Fluxes*, vol. 2, pp. 339–368. Dordrecht: Kluwer Academic Publishers.

Graf J, Sasaki C, *et al.* (1998) NASA Scatterometer Experiment. *Asta Astronautica* 43: 397–407.

Gruber A, Su X, Kanamitsu M and Schemm J (2000) The comparison of two merged rain gauge-satellite precipitation datasets. *Bulletin of the American Meteorological Society* 81: 2631–2644.

Katsaros KB (1980) Radiative sensing of sea surface temperatures. In: Dobson F, Hasse L and Davies R (eds) *Instruments and Methods in Air–sea* Interaction, pp. 293–317. New York: Plenum Publishing Corp.

Katsaros KB, DeCosmo J, Lind RJ *et al.* (1994) Measurements of humidity and temperature in the marine environment. *Journal of Atmospheric and Oceanic Technology* 11: 964–981.

Kummerow C, Barnes W, Kozu T, Shiue J and Simpson J (1998) The tropical rainfall measuring mission (TRMM) sensor package. *Journal of Atmospheric and Oceanic Technology* 15: 809–817.

Liu WT (1990) Remote sensing of surface turbulence flux. In: Geenaert GL and Plant WJ (eds) *Surface Waves and Fluxes*, vol. 2, pp. 293–309. Dordrecht: Kluwer Academic Publishers.

Parker SP (ed.) (1977) *Encyclopedia of Ocean and Atmospheric Science*. New York: McGraw-Hill.

Pinker RT and Laszlo I (1992) Modeling surface solar irradiance for satellite applications on a global scale. *Journal of Applied Meteorology* 31: 194–211.

Reynolds RR and Smith TM (1994) Improved global sea surface temperature analyses using optimum interpolation. *Journal of Climate* 7: 929–948.

List RJ (1958) *Smithsonian Meteorological Table*s, 6th edn. City of Washington: Smithsonian Institution Press.

van der Meulen JP (1988) On the need of appropriate filter techniques to be considered using electrical humidity sensors. In: *Proceedings of the WMO Technical Conference on Instruments and Methods of Observation (TECO-1988)*, pp. 55–60. Leipzig, Germany: WMO.

Wentz FJ and Smith DK (1999) A model function for the ocean-normalized radar cross-section at 14 GHz derived from NSCAT observations. *Journal of Geophysical Research* 104: 11 499–11 514.

SENSORS FOR MICROMETEOROLOGICAL FLUX MEASUREMENTS

J. B. Edson, Woods Hole Oceanographic Institution, Woods Hole, MA, USA

doi:10.1006/rwos.2001.0330

Introduction

The exchange of momentum, heat, and mass between the atmosphere and ocean is the fundamental physical process that defines air–sea interactions. This exchange drives ocean and atmospheric circulations, and generates surface waves and currents. Marine micrometeorologists are primarily concerned with the vertical exchange of these quantities, particularly the vertical transfer of momentum, heat, moisture, and trace gases associated with the momentum, sensible heat, latent heat, and gas fluxes, respectively. The term flux is defined as the amount of heat (i.e., thermal energy) or momentum transferred per unit area per unit time.

Air–sea interaction studies often investigate the dependence of the interfacial fluxes on the mean meteorological (e.g., wind speed, degree of stratification or convection) and surface conditions (e.g., surface currents, wave roughness, wave breaking, and sea surface temperature). Therefore, one of the goals of these investigations is to parametrize the fluxes in terms of these variables so that they can be incorporated in numerical models. Additionally, these parametrizations allow the fluxes to be indirectly estimated from observations that are easier to collect and/or offer wider spatial coverage. Examples include the use of mean meteorological measurements from buoys or surface roughness measurements from satellite-based scatterometers to estimate the fluxes.

Direct measurements of the momentum, heat, and moisture fluxes across the air–sea interface are crucial to improving our understanding of the coupled atmosphere–ocean system. However, the operating requirements of the sensors, combined with the often harsh conditions experienced over the ocean, make this a challenging task. This article begins with a description of desired measurements and the