

## The MR: a Meteorological Data Sensing, Recording and Telemetry Package for Use on Moored Buoys\*

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### ABSTRACT

A new meteorological sensing, recording, and telemetry package based on digital data processing techniques has been developed for long-term (6-month) deployments on surface buoys moored in the ocean. Data are recorded on magnetic cassette tapes and telemetered via satellite and Service Argos. Sensors for measuring vector-averaged wind speed and direction, air and water temperatures, relative humidity, solar radiation, and barometric pressure were selected for accuracy and reliability. Except for relative humidity, performance of the sensors has been excellent. Results of ship-to-buoy comparisons of wind speed and air temperature sensors show agreement within the basic ship sensor accuracies, i.e.,  $0.1 \text{ m s}^{-1}$  and  $0.4^\circ\text{C}$ .

### 1. Introduction

Within the last 10 years, interest in air-sea interaction and, in particular, in understanding the response of the upper layers of the ocean to the atmosphere, has increased markedly. Instruments like the Vector Measuring Current Meter (VMCM) have provided the capability to make long time series of current measurements in the top tens of meters under surface buoys. Efforts have also been undertaken to provide the capability of directly measuring local atmospheric forcing.

In 1972, the Vector Averaging Wind Recorder (VAWR) was developed from the Vector Averaging Current Meter (VACM) (Payne, 1974) and deployed in JASIN-72 (Joint Air-Sea Interaction experiment). The VAWR recorded vector averaged wind speed and direction, air and sea temperatures, relative humidity, barometric pressure, and solar radiation. Halpern et al. (1974) reported the development of a similar instrument. In the late 1970s and 1980s the Buoy Group at the Woods Hole Oceanographic Institution (WHOI) made substantial improvements in this instrument and deployed several in experiments. The VAWR suffers from a lack of flexibility, however; it is difficult and expensive to add more sensors and satellite telemetry, and its shape, similar to that of the VACM, is difficult to mount on typical buoys.

In 1981, the availability of alternative, commercially produced meteorological data recorders was examined.

Several companies offered systems but all either required too much power or lacked flexibility. In 1982 we began a program to develop a buoy-mounted meteorological sensing and recording package. The first SEQUAL (Seasonal Equatorial Atlantic experiment) (Anon, 1983) moorings, scheduled in January 1983, were targeted as the first use of the instrument. In this paper we report on the design, choice of sensors, electronics, and first deployments of the Meteorological Recorder (MR).

### 2. Design considerations

The size of surface buoys commonly used for oceanographic research places severe power restrictions on the sensors and electronics which can be considered for long deployments. Our goal was to produce a system which could measure the parameters required to compute wind stress and surface heat fluxes (except for long wave radiation), both record all the data and transmit a subset via satellite telemetry, and have a duration of at least 6 months on a 3 m toroidal buoy. The standard parameters include vector-averaged wind speed and direction, air and sea temperatures, relative humidity, barometric pressure, and solar radiation. All the sensors are readily available commercially.

The design of both hardware and software was planned to be quite modular so that changes in almost any part of the system could be made with a minimum of effort. A few examples of the flexibility that resulted are as follows: we are using two different Argos transmitters with different data format and control line requirements; systems with up to three sensors in addition to the standard suite have been deployed and almost any number of analog or digital sensors could be

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incorporated; and any of a number of data storage media could be substituted for the cassette recorder now in use. This modularity will allow us to upgrade conveniently as better components appear.

Choice of Argos as the telemetry medium was made primarily for its positioning capabilities. Data transmission capacity is modest; 256 bits each time a satellite passes within range, or six to seven times a day on the equator. The positioning has proved invaluable. In one SEQUAL recovery, the buoy went adrift the day before the ship reached the mooring to recover it. Buoy positions from Service Argos allowed the ship to track down and recover the buoy with no lost gear and a minimum of lost time. In several cases where the buoy sank or disappeared, the data recorded by Service Argos were the only data recovered although the time series were not nearly as satisfactory as internally recorded data.

Figure 1 is a sketch of the package mounted on the type of toroid buoy it has been deployed on most often. On the two vertical posts are the wind processor with anemometer and the Argos antenna with pyranometer mounted integrally on the top. On the top shelf are two radiation shields containing air temperature and relative humidity sensors. On the third shelf is the electronics/battery unit. The water temperature sensor is attached to one leg of the buoy's rigid bridle. The square plate mounted on one leg of the buoy is a vane to orient it in the wind.

### 3. Overview of MR design and operation

At the heart of the system is a set of microprocessor-based digital circuitry which acts as the system controller. It controls the timing of all the operations, takes data from the sensors, digitizes it if in analog form, averages it, reformats it, and presents it to a cassette recorder and an Argos transmitter.

The system components, shown in the block diagram in Fig. 2, can be broken down into three categories: digital data logger, sensors, and power source. The digital data logger (DDL) consists of the digital controller and computation circuitry, analog signal conditioning and digitizing circuitry, a cassette tape recorder, an Argos transmitter and antenna, and the power supply circuitry. Outputs of the air and water temperature thermistors, solar radiation pyranometer, and relative humidity sensor are processed by the analog-to-digital conversion sections. The barometer and wind processor transmit digital data to the DDL.

The heart of the Digital Data Logger (DDL) is the CPU-800A board,<sup>1</sup> based on the NSC-800 microprocessor. This chip uses the Z-80 instruction set with extensions added for hardware interrupts and the use of power saving modes. The other circuit boards include

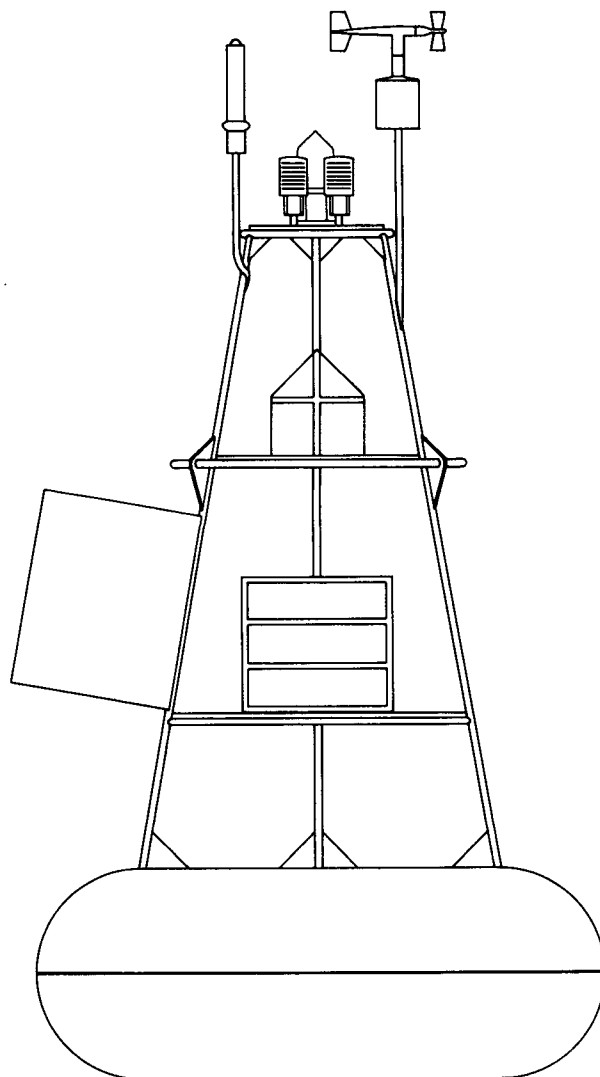


FIG. 1. Sketch of the meteorological recorder with sensors mounted on a toroid buoy.

an Onset or Quartic Systems communication board, a WHOI-built 12-bit A/D (analog-to-digital) conversion board, and two WHOI-built peripheral interface boards. One of these interface boards conditions the analog sensor outputs to match them to the input requirements of the A/D converter while the other handles the interfacing to the output devices.

The DDL program is a concise timing control program which manages the flow of data from sensors with analog or digital outputs to the storage and telemetering devices with minimal processing. It is organized as a set of well-defined subroutines written in Z-80 assembly language and using the NSC-800 extensions. The program takes advantage of the two power conserving modes of the NSC-800 wherever possible. Substantial changes in sampling schemes and recording

<sup>1</sup> Manufactured by the Onset Computer Corporation.

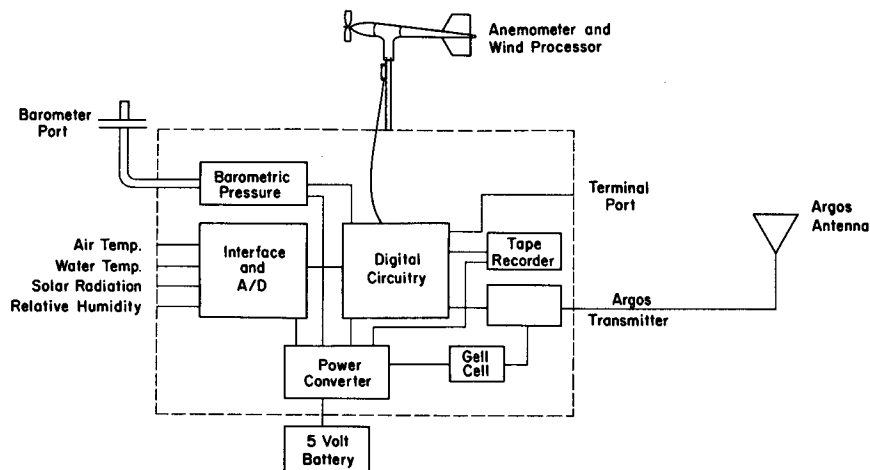


FIG. 2. Block diagram of the meteorological recorder.

intervals can be made simply by changing the initialization parameters.

The MR is self-starting. The operator connects power 15 s before the starting time of the first recording interval, and the program in the microprocessor memory does the rest. The data string which goes to the tape recorder is also sent to an RS-232 port, with a waterproof connector to the outside of the case, where the data can be monitored with a standard computer terminal. Proper functioning of all parts of the MR, except the tape recorder and Argos transmitter, can thus be verified directly at any time prior to deployment. Further verification can be obtained with a local Argos receiver.

Fail-safe procedures are included for all the data sources. If data are not received from the A/D converter, the wind processor, or the barometer within specified waiting periods, or if the data are not taken by the output devices, the program continues. In this way, the meteorological recorder can continue to operate with whatever sections are functioning in spite of a partial failure.

In a typical deployment, the analog sensors are sampled 64 times per 7.5 min recording interval, or once per 7 s. Since the time constant of each of the sensors is 10 s or greater, aliasing is avoided.

The Argos transmitter transmits the averages from the previous recording interval every 60 s. Parameters transmitted are wind speed and direction (computed from the 7.5 min vector averaged components), analogs of barometric pressure, air and water temperatures, solar radiation, relative humidity, battery voltage, and any other parameters being monitored, such as mooring tension.

For most of our deployments we have used Carbon-aire air-zinc batteries manufactured by McGraw-Edison which provide 1000 amp-h at 2.5 V. They are smaller, lighter, and considerably less expensive than

an equivalent alkaline-zinc battery. A high efficiency power converter changes 5 V from two of these batteries in series to the 12 V required. A gel cell provides the transient currents drawn by the transmitter and tape recorder.

The most common failures in the system in early deployments were in the electrical connections between sensors and the DDL. The use of Seacon underwater connectors was an effective solution.

#### 4. Wind processor

The wind processor (WP) includes an R. M. Young model 5103 integral propeller/vane anemometer and a stainless steel housing containing a Digicourse model 225/01 magnetic compass, an Onset CPU6805A microprocessor board and a circuit board to interface the anemometer propeller and vane and the compass to the CPU6805A board. Mounting compass and anemometer as a single mechanical unit with the electronics allows us to align compass and vane in an area free of distortion of the earth's magnetic field, i.e., in the middle of a field instead of on a buoy set up on a ship.

The wind processor (WP) vector averages the wind continuously except for a few microseconds during each recording interval when it is transferring data to the DDL. Each propeller revolution produces an electrical pulse which initiates a computation cycle. The vane position is read, its value added to the current compass value (updated each 15 s), and the equivalent of the cosine and sine of the sum added to the two summing buffers. Since the propeller makes 1 revolution per 30 cm of air, a zephyr of  $1 \text{ m s}^{-1}$  results in about 3 complete cycles per second. Since the computation rate is proportional to the wind speed, the wind processor is able to resolve and average the apparent wind induced by buoy pitch and roll as well as

the part of the turbulence spectrum that the anemometer can sense. The 15-s compass sampling period is a compromise chosen to conserve electrical power without compromising data quality significantly. The time constant of the compass is in the range of 5–10 s. Thus, we are undersampling the buoy heading by about a factor of 2.

## 5. Sensors

### a. Wind speed and direction

We chose to measure wind speed and direction with an integral propeller and vane because an integral unit is easier to mount on a small buoy than separate cups and vane, and because the propeller offers better cosine response than cups to winds above or below the horizontal plane of the anemometer (Busch et al., 1980).

An early version of the R. M. Young model 5103 wind monitor showed potential for performing accurately and reliably, although the admission of salt water to a bearing containing two different grades of stainless steel led to corrosion problems. The problem was solved by switching to bearings with plastic ball retainers. We routinely replace bearings and vane potentiometers after each deployment and have experienced no failures. Recently purchased units contain a number of improvements including longer life potentiometers and sealed bearings, but we have not tested the sealed bearings.

The model 5103 has an 18 cm, 4 bladed, Gill-designed helicoidal propeller injection molded of polypropylene. A magnetic disk on the end of the propeller shaft produces a pulse in a coil with each propeller revolution (the standard model produces 3 pulses per revolution). The anemometer is housed in an injection molded plastic vane, with an orientation sensed by a potentiometer linear to 0.25%. Manufacturer's specifications for the propeller and vane are given in Table 1. The repeatability of an injection molded propeller makes it unnecessary to calibrate anemometers as long as bearings are kept in good condition. We have found that, although the pitch of the propeller is 30 cm, the

calibration data in the anemometer manual are best fitted by

$$WS = 0.293\nu + 0.2$$

where WS is the windspeed in meters per second and  $\nu$  is the rotation rate in per seconds.

The anemometer is mounted 32 cm above a housing containing electronics and compass so that the effect of the housing on the airflow past the anemometer is minimal. The compass and anemometer both have keyed mountings to the wind processor chassis and case giving a known orientation between compass and vane. Instantaneous wind direction is then the sum of the digital compass output and the digitized vane potentiometer value. The Digicourse model 225 8-bit gray coded magnetic compass has internal gimbals to allow it to tilt up to 38° and an oil-filled housing for viscous damping. The effective damping time constant is 5–10 s, depending on how it is measured.

### b. Air and water temperatures

Air and water temperature sensors are standard YSI thermistors, nominally 30 000  $\Omega$  at 20°C (YSI P/N 44032), potted into 1/4-20 bolts by YSI (probe style number 095). The thermistors are calibrated to 0.01°C accuracy in a WHOI facility before each deployment. They are mounted in a Delrin cylinder which provides protection for the thermistor probe and for the connections to the cable. There have been no temperature sensor failures.

The air temperature probe screws into the base of an R. M. Young model 41001 Gill Multiplate/Free Flow radiation shield to protect it from shortwave solar heating. This shield is probably as good as any non-aspirated shield although substantial heating (1°–3°C) can take place at low wind speeds and high sun angles. For wind speeds greater than 5 m s<sup>-1</sup> in the tropics we see day–night temperature differences typically less than 0.5°C. Some if this is due to diurnal heating of the surface water but an unknown portion of it may be due to solar heating of the radiation shield.

The water temperature probe screws into another Delrin cylinder which allows it to be strapped to a leg of the buoy's rigid bridle with nylon ties about 1 m below the water line. Uncertainties in the analog signal conditioning, analog-to-digital conversion, and cable resistance raise the overall uncertainty in water temperature measurements to 0.02°C.

### c. Relative humidity

Latent heat flux is a function of absolute humidity, which can be related to relative humidity. Since the latent heat flux is commonly of the order of ten times larger than the sensible heat flux, accurate estimates of the total heat flux depend critically on the accuracy of the relative humidity (RH) measurements. Under typical conditions in the tropics, uncertainty of 5% RH

TABLE 1. R. M. Young model 5103 propeller and vane characteristics.

Characteristic	Value
<i>Propeller</i>	
Threshold sensitivity	0.3 m s <sup>-1</sup>
Distance constant (63% recovery)	3.3 m
Calibration	1 turn per 30 cm of air
<i>Vane</i>	
Threshold sensitivity	1.0 m s <sup>-1</sup>
Delay distance (50% recovery)	1.3 m
Damping ratio	0.23
Damped natural wavelength	7.2 m
Range	0°–352°

leads to about 10% uncertainty in latent heat flux. With present technology, 5% RH accuracy is probably not possible in long-term deployments but 10% RH may be. The inaccuracy stems from two sources, basic instability in the sensor and imperfect protection of the sensor from salt.

A number of sensors are on the market which consist of a thin polymer film between two metal electrodes. Moisture content of the polymer stays in equilibrium with that in the surrounding air. Changes in moisture content are detected by the resulting changes in the dielectric constant or resistance. The sensor is thus used as either a capacitor or resistor in the detection circuit. Although the measurement is indirect, such sensors are commercially available, convenient to use, and relatively inexpensive.

We have used the Väisälä Humicap sensor exclusively since it seemed to be the most suitable sensor of its type for buoy deployments. It converts capacitance changes in the sensor to an output voltage nearly linear in relative humidity. A third degree equation fits the data from a typical calibration to about 0.5% RH. Väisälä states the accuracy as 2%, but we have found shifts of up to 5% RH with repeated calibrations of the same sensor over a period of 6 months. One disadvantage of the Humicap circuit is the stringent power supply requirements, 10 ma at  $3.60 \pm 0.01$  V.

Protecting any humidity sensor from salt is essential for meaningful data. A minute amount of conducting material on the Humicap sensor surface can cause a serious calibration shift, and more material can cause sensor failure. Surrounding the sensor with a shield on which salt could accumulate would also result in inaccurate observations. Clarke and Painting (1983) describe success with a membrane of polytetrafluoroethylene (PTFE) made by Gore Tex. This film is available in average pore sizes of 0.02 to 45 microns. Choice of a pore size is a compromise between flushing rate of the sensor cavity and the possibility of salt particles getting through the membrane. Clarke and Painting used a pore size of 0.02 microns. We have protected the Humicap element with Gore Tex with 0.45 micron pore size in all of our deployments. Examination of the sensor element upon recovery has shown that the cap has been effective in preventing salt from reaching the sensor. Since a solar-induced increase of air temperature inside the shield would result in an apparent decrease in relative humidity, the probe is mounted in an R. M. Young multiplate radiation shield like that for the air temperature thermistor.

Although the convenience of capacitance sensors is appealing, our use of the Humicap has not been successful. Out of 14 deployments of the Väisälä Humicap in which we recovered the MR, only two have returned reliable data for the entire 6-month deployment. In the rest there were calibration changes or failures of the Humicap sensor element or electronics. Although the two successful deployments occurred in the most recent

MR deployments and used a recently introduced, redesigned sensor element, we must conclude that, in its present form, the Humicap is not a viable sensor for long ocean deployments. It seems likely a more inherently stable sensor is needed. A group at WHOI is currently adapting a chilled mirror dewpoint device for use on buoys.

#### *d. Barometric pressure*

Barometric pressure is measured with an AIR model DB barometer. The aneroid element is sensed capacitively, the result is digitized, and an internal microprocessor applies calibration coefficients, correcting for the temperature sensitivity. It then converts to a number of jumper selectable digital output formats. We use a parallel binary output with pressure in millibars and have configured our units to present an average of 1000 samples over 100 s to the DDL once per recording interval. This is sufficient to average out the effects of vertical buoy motion.

Long-term accuracy of the model DB is stated by AIR as 100 Pa for 1 yr. The barometer has been trouble-free during our deployments although a few early production units failed while in our laboratory. Some modifications (and updated older barometers) have been made by AIR which seem to have improved reliability and long-term stability. In FASINEX, our most recent deployment, the five AIR barometers were completely reliable and experienced calibration shifts of approximately 100 Pa or less over a 1-yr period which included the 6-month deployment. On a buoy, the measurement accuracy is usually limited by the dynamic effects of the wind. To minimize these, we use a port designed by Gill (1976). Gill's wind tunnel tests indicate that we can expect errors of 20 Pa or less in a  $20 \text{ m s}^{-1}$  wind, increasing at higher wind speeds. Note that this error is always a negative bias.

#### *e. Solar radiation*

To measure shortwave downward flux (solar irradiance), we use the Eppley model 8-48 pyranometer shown mounted on top of the Argos antenna in Fig. 1. This is a thermopile device with a time constant of 5 s and accuracy of about  $\pm 3\%$ . Shortwave energy flux into the ocean can be computed using the albedo results of Payne (1972).

Errors due to buoy motion can arise from either pitch and roll or mean tilt, the amount of error depending on sea and cloud conditions. In an unpublished study of a large number of photographs of toroid buoys, taut-line moored with rigid bridles, we observed that only rarely do the buoys tilt as much as  $10^\circ$ .

In an extensive analysis of the errors in measuring irradiance at sea, Katsaros and DeVault (1986) estimated that errors in daily average irradiance could be as large as  $\pm 20\%$  for latitudes greater than  $45^\circ$  and a

mean tilt of  $10^\circ$ . Without measurements of buoy tilt, amplitude, and azimuth, it is difficult to assess the uncertainty in our measurements. By observation of the buoys at sea we feel that the mean buoy tilt is less than  $5^\circ$ . For latitudes less than  $45^\circ$ , the uncertainty in the daily mean irradiance is probably of order  $\pm 10\%$  or less.

Accumulation of salt spray on the pyranometer is of concern. Our experience, however, is that it is not a problem under most conditions. Small amounts of salt particles on the protecting glass hemisphere will scatter light somewhat but will not significantly reduce the amount of energy reaching the sensor surface. In conditions when there is much spray in the air, the salt seems to be washed off as fast as it accumulates.

The pyranometer is mounted on top of the Argos antenna where it cannot be shaded. The 400 MHz antenna output does not affect the pyranometer output and we have seen no attenuation of radiated power from the antenna.

We have experienced no failure of the Eppley pyranometers and any changes in calibration constants have been within the 3% accuracy of the instrument.

## 6. Deployments

Seventeen MRs have been built and used in a total of 22 deployments in the SEQUAL, Tropic Heat (Eriksen, 1985) experiments and FASINEX (Stage and Weller, 1985, 1986). Five have been lost with their moorings and one suffered serious damage from the collision of an unknown ship (which left green paint behind). Other problems have been caused most frequently by the harsh environment of a surface buoy.

In the Atlantic Ocean there is an annual event which showed up quite well in the SEQUAL data (Payne, 1984). Wind and temperature from SEQUAL moorings SA5 and SA6 are shown in Fig. 3. The moorings were located at  $0.05^\circ\text{N}$ ,  $24.00^\circ\text{W}$  and  $0.01^\circ\text{N}$ ,  $14.03^\circ\text{W}$ , respectively. A wind relaxation event in late March and a subsequent increase in wind speed in early April are apparent in the plots. Within the limitations in time resolution caused by higher frequency wind speed fluctuations, the events occur simultaneously at the two locations in spite of a separation of  $14.44^\circ$  of longitude. An increase of several degrees in the water temperatures during the period of low winds is accompanied by a concomitant peak in air temperature. The SA6 data were cut short by the ship collision mentioned above.

## 7. Buoy-ship comparisons

On four MR deployment cruises, comparisons were made between MRs on the buoys and instruments mounted on the ships. Table 2 lists information about the ship and MR data. On each of the ships we mounted an R. M. Young model 8002 propeller/vane anemometer and an EG&G Model 220 Environmental Moni-

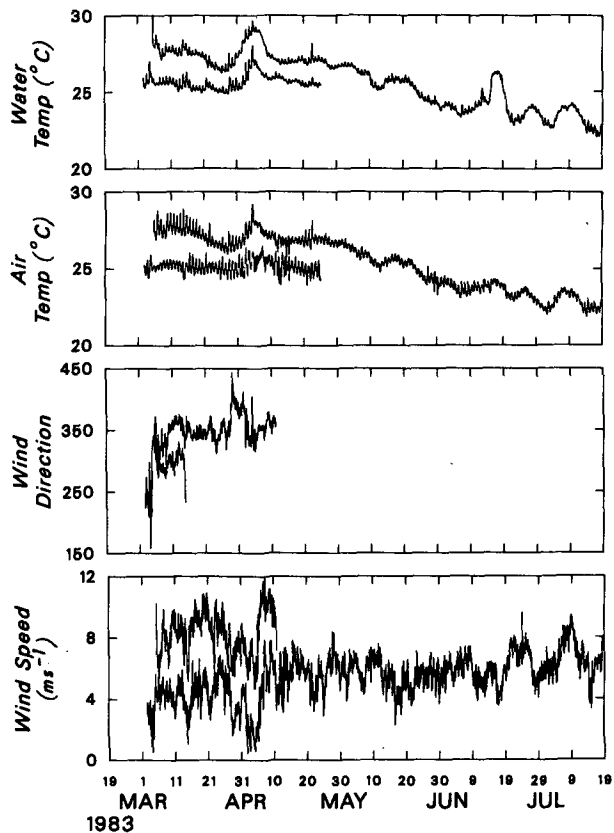


FIG. 3. Wind speed and direction, air temperature, and water temperature from two Meteorological Recorders deployed in SEQUAL I. Vertical offsets are as follows: wind speed,  $5 \text{ m s}^{-1}$ ; wind direction,  $20 \text{ deg}$ ; air temperature,  $2^\circ\text{C}$ ; water temperature,  $2^\circ\text{C}$ .

toring System consisting of aspirated air and dewpoint temperature sensors. The EG&G model 220 did not work at all times and the MRs did not all have a full suite of sensors. Table 2 lists the parameters recorded for each comparison on both systems.

On the R/V *Endeavor*, the sensors were mounted on a vertical mast stepped about 1 m aft of the peak of the bow. The sensors were located 7 m above the rail, putting them 14.7 m above the ship's water line. On the R/V *Discoverer* and R/V *Researcher*, they were mounted on brackets attached at the top of the jackstaff which, in both cases, was less than 2 m aft of the peak of the bow. On these two ships the sensors were 4–5 m above the rail and 14–15 m above the water line. Data were used in a comparison only when the ship's bow pointed within  $20^\circ$  of the wind direction and when the ship was moving less than  $0.5 \text{ m s}^{-1}$  relative to the buoy. Ship-buoy separation was kept to less than 1 km in all cases. To correct for absolute ship speed, range and bearing on the buoy were taken at frequent intervals using the ship's radar and a time series of ship speed and direction was developed for each comparison period. Because of the location of the sensors on each

TABLE 2. Comparisons between MRs on four deployment cruises.

Ship/comparison	Sensor height (m)	Parameters recorded†	Date	Experiment
<i>Endeavor</i>	10.5	WS, WD, AT, DP	April 1983	LOTUS V
1	3.5	WS, WD, AT, WT, SR, BP		
2	3.5	WS, WD, AT, WT, SR, BP		
3	3.5	WS, WD, AT, WT, SR, BP		
<i>Discoverer</i>	14.8	WS, WD, AT, WT	October 1983	Tropic Heat
4	3.5	WS, WD, AT, WT, SR, RH		
5	3.5	WS, WD, AT, WT		
6	3.5	WS, WD		
<i>Researcher</i>	13.7	WS, WD, AT, WT, DP*	April 1984	Tropic Heat
7	3.5	WS, WD, AT, WT, RH		
8	3.5	WS, WD, AT, WT, SR		
9	3.5	WS, WD, AT		
<i>Melville</i>	13.0	WS, WD, AT, DP	November 1984	Tropic Heat
10	3.5	WS, WD, AT, WT, RH, SR		
11	3.5	WS, WD, AT, WT, RH, SR, BP		

- † WS scalar averaged wind speed.  
 WD ship: scalar averaged vane direction.  
 buoy: vector averaged wind direction.  
 AT air temperature.  
 WT water temperature.  
 DP dewpoint temperature.  
 RH relative humidity.  
 SR solar irradiance.  
 BP barometric pressure.  
 \* Ship DP for 7 and 8 only.

ship and the attention given by the ships' officers to maintaining a fixed position relative to the buoy, the data are only minimally affected by motion of the ships.

The MR data for eight of the comparisons were taken from the tape-recorded data after mooring recovery and standard data processing. Although four of the Tropic Heat buoys sank, data were recovered from the three units ultimately recovered. Data from the remaining comparison, number 4, were taken from the Argos transmissions from the buoy recorded on the

ship. Because ship direction could not be recorded and there was likely to be a substantial difference between vector-averaged directions from the buoy and scalar averaged vane directions from the ship, we do not compare the two sets of directions here.

#### a. Wind speed comparisons

Since the processing and recording unit used on the ships was capable of computing scalar averages only,

TABLE 3. Wind speed comparison results.

Ship/comparison	No. data points	Duration (h)	Buoy wind speed	Ship wind speed	Difference	Buoy S/V	Sea (ft)	Swell (ft)
<i>Endeavor</i>								
1	36	1.2	9.99	11.09	-1.09	1.08		
2	75	2.5	7.86	7.96	-0.10	1.08		
3	41	1.4	9.55	10.49	-0.94	1.08	8-10	
<i>Researcher</i>								
4	17	2.1	4.19	4.13	0.06	1.12	2	7
5	28	3.5	3.60	3.69	-0.09	1.18	0	5
6	5	0.6	7.33	7.75	-0.42	1.88	3	7
<i>Discoverer</i>								
7	5	5.0	6.00	6.07	-0.07	N/A	1	2
8	11	5.0	6.90	7.06	-0.16	1.07	3	0
9	11	5.0	8.91	8.56	0.35	1.07	3	2-4
<i>Melville</i>								
10	8	1.0	7.62	7.51	0.11	1.16	3	
11	25	3.1	8.97	8.74	0.23	1.21	3	

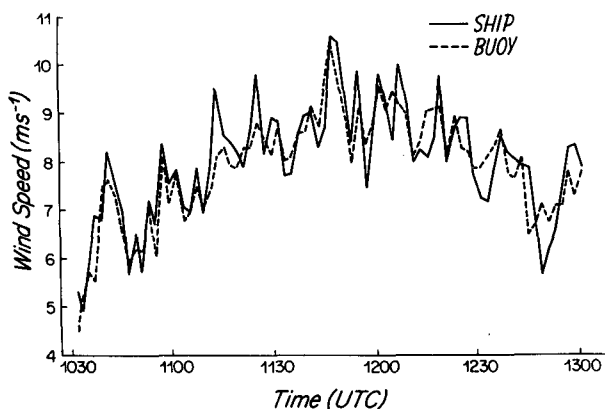


FIG. 4. Wind speed; comparison 2.

we will compare wind speed averages between ship and buoy. The MR data show that scalar-averaged wind speeds from the buoys are about 10% higher than vector averages, the difference being caused by both natural fluctuations in wind speed and direction and buoy motion. The ratio of scalar to vector averaged wind speed for the buoy winds is listed for each comparison period. We expect that the effects of ship motion on the scalar average will vary with sea state and swell direction and amplitude.

All wind speeds were corrected to 10 m altitude using the methods described in Large and Pond (1982). This required air and sea temperatures and humidity. Where all the parameters were available from a platform they were used to correct the wind speeds from that platform. If a parameter was not available, for example, dewpoint temperatures on the ship system, the appropriate parameter from the other platform was substituted.

Results of the wind speed comparison are summarized in Table 3 and require some interpretation. In comparisons 2 and 7, the averaging and recording interval is sufficiently small to resolve the major fluctuations and conditions are fairly uniform over spatial scales larger than the ship-buoy separation. Comparison 2 in Fig. 4 is a good example with high-frequency fluctuations superimposed on low-frequency changes. The high correlation between ship and buoy signals is apparent. The ship was stationed directly downwind of the buoy.

Comparison 5, shown in Fig. 5, has a small mean difference by chance. Although the ship and buoy sensors have recorded similar sorts of fluctuations it is impossible to say without a much longer record whether they are the same signal out of phase or whether the two signals are uncorrelated. The buoy was kept abeam of the ship during this comparison. Comparisons 6, 8, 10, and 11 are similar.

Comparisons 4 and 9 were made while rapid changes were occurring in the meteorological conditions. Figure 6 shows comparison 9. With the speed and magnitude of the changes it is not surprising that ship and buoy responses seem to be 10–15 min out of phase.

Comparisons 1 and 3 likely have large differences due to a different mechanism. Comparison 1, in Fig. 7, shows a fairly high correlation between ship and buoy wind but the ship wind is almost always higher. We believe this is a result of the wave height. In waves of 3 m amplitude, as estimated by the bridge, the anemometer is on a level with surrounding wave crests when the buoy is in a trough. Under these conditions, the anemometer sees a mean wind less than that well above the wave crests.

Figures 8 and 9 are scatter plots of buoy vs ship winds, including all the comparison data. Comparisons 1 and 3 appear in Fig. 9; the rest appear in Fig. 8. The broken line in both represents a slope of 1. It appears, in general, that there is excellent agreement between ship and buoy winds for speeds up to about  $8 \text{ m s}^{-1}$ . As wind speed and resulting wave height continue to increase, an anemometer mounted at 3.5 m height begins to underestimate the true wind speed at wind speeds of 8 to  $9 \text{ m s}^{-1}$ . Two general conclusions can be drawn from this: buoy anemometers should be mounted as high as possible if good results are required at high wind speeds, and buoy wind data at high wind speeds should be used with caution.

For conditions in which the comparisons were valid, i.e., where the wind fluctuations were uniform over sufficiently large spatial scales and where the waves were not too large, the ship and buoy anemometers agreed to within  $0.1 \text{ m s}^{-1}$ . This does not necessarily imply that the absolute accuracy of the wind speed measurements is of this order since we do not know what the effects of the presence of the ship and its motion are on the ship measurements. Indeed, we expect the buoy to be inherently a good platform so the measurements

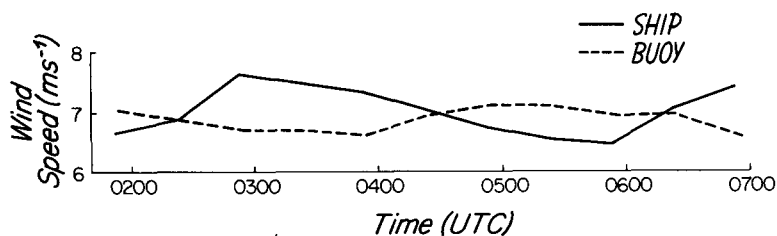


FIG. 5. Wind speed; comparison 5.



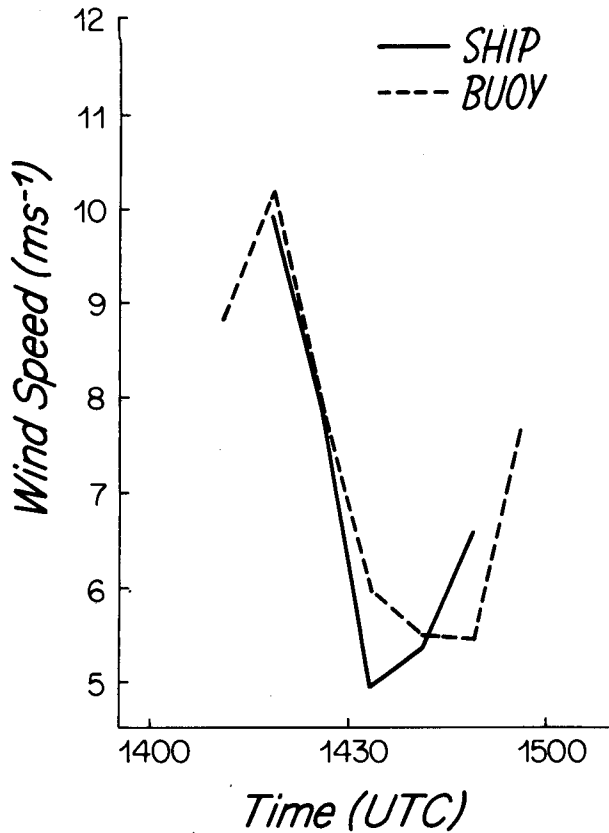


FIG. 6. Wind speed; comparison 9.

may say more about the feasibility of making good wind measurements from a mast in the bow of a ship than about the quality of the buoy measurements. It is reassuring that they are, at least, consistent.

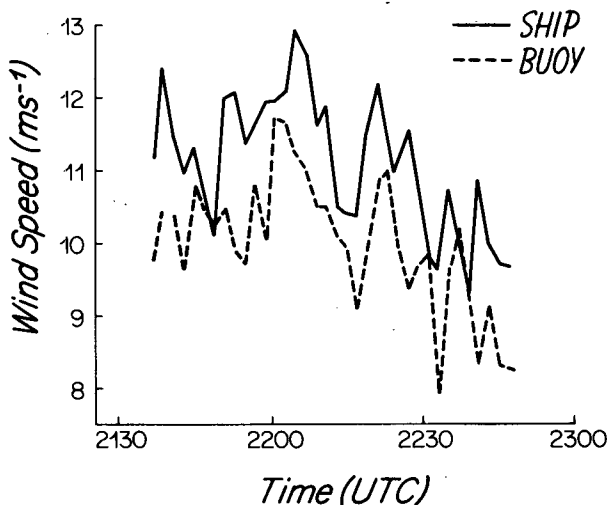


FIG. 7. Wind speed; comparison 1.

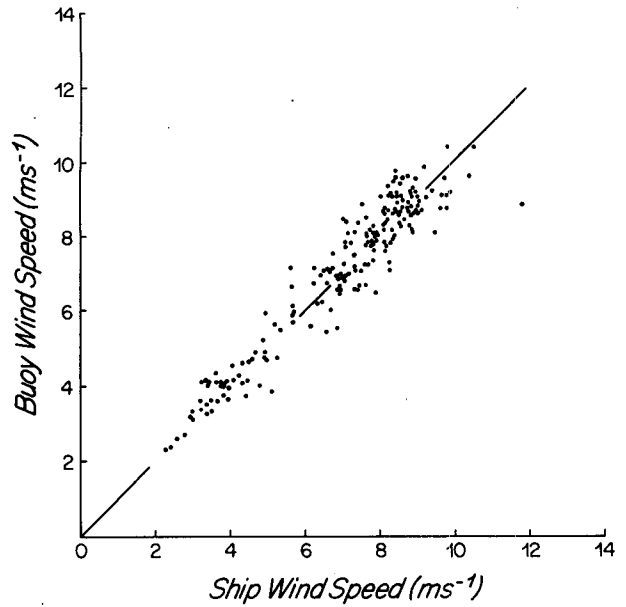


FIG. 8. Buoy vs ship wind speed; comparisons 2 and 4-11.

*b. Air temperature*

Several inadequacies in the air temperature data preclude an extensive analysis. First, the accuracy of the temperatures measured with the EG&G model 220 are stated by the manufacturer as  $0.4^{\circ}C$ . We expect that the MR air temperatures are more accurate than this, certainly at night. Second, the R. M. Young radiation shield used to protect the MR air temperature thermistor from solar radiation is less than perfect.

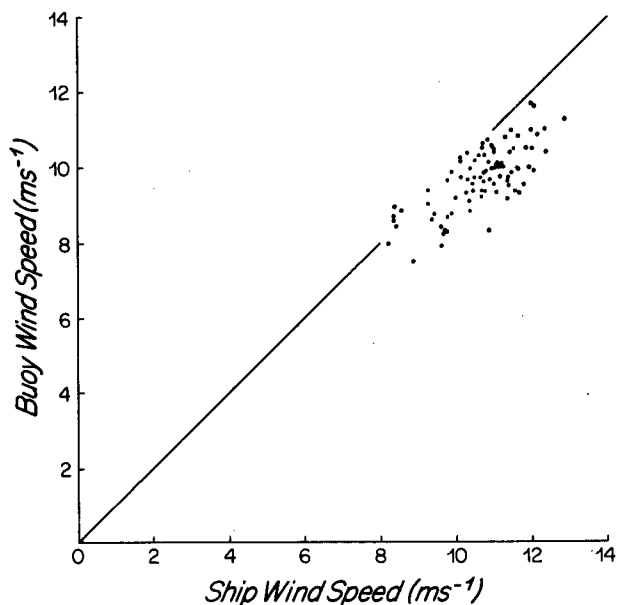


FIG. 9. Buoy vs ship wind speeds; comparisons 1 and 3.

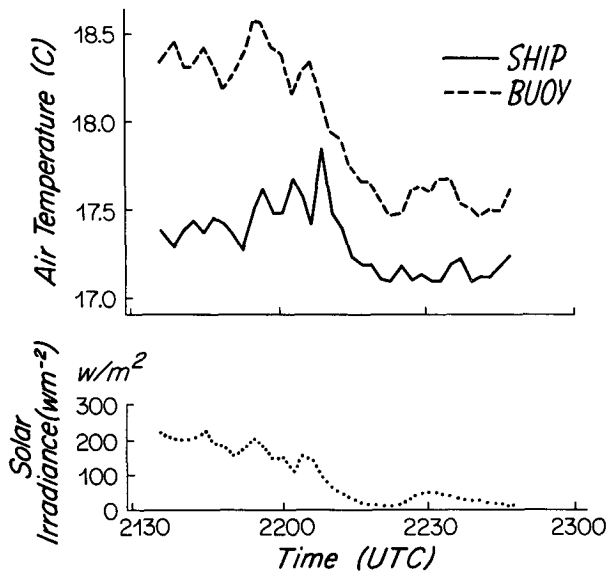


FIG. 10. Air temperature; comparison 1.

Figure 10 shows the air temperature and solar radiation from comparison 1. The temperature difference decreased from about 1.0°C at a solar irradiance of 200 W m<sup>-2</sup> to about 0.5°C at values near 0 W m<sup>-2</sup>. The amount of solar heating of the MR thermistor is a function of solar irradiance and wind speed. An air temperature correction factor for the Young radiation shield may be possible but there are not enough data in the ship-buoy comparisons to make any estimates of the correction. Of the five remaining nighttime comparisons, one used Argos data with nominal thermistor calibrations resulting in insufficiently accurate air temperatures from the MR. We are then left with the four comparisons summarized in Table 4. The air temperatures have been adiabatically corrected to 10 m altitude.

The mean differences are all within the 0.4°C accuracy of the EG&G model 220. A typical record is comparison 2 shown in Fig. 11. The single example of measurements under rapidly changing conditions is comparison 9 in Fig. 12. The small mean difference may be fortuitous in this case, in view of the differences in the signals at the two platforms.

Thus, in nighttime conditions, air temperatures from

TABLE 4. Air temperature comparison results.

Ship/comparison	No. data points	Duration (h)	Ship AT (°C)	Buoy AT (°C)	Difference
Endeavor/2	75	2.5	16.27	16.60	0.33
Discoverer/9	11	5.0	24.82	24.71	-0.11
Melville/10	8	1.0	23.96	23.74	-0.22
Melville/11	25	3.1	24.33	24.16	0.17

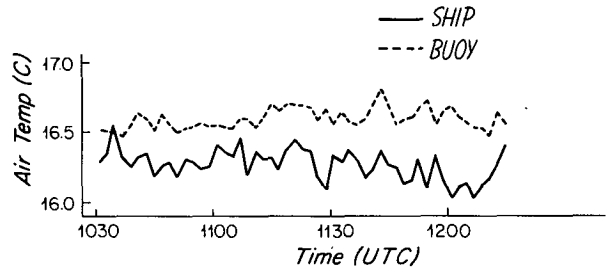


FIG. 11. Air temperature; comparison 2.

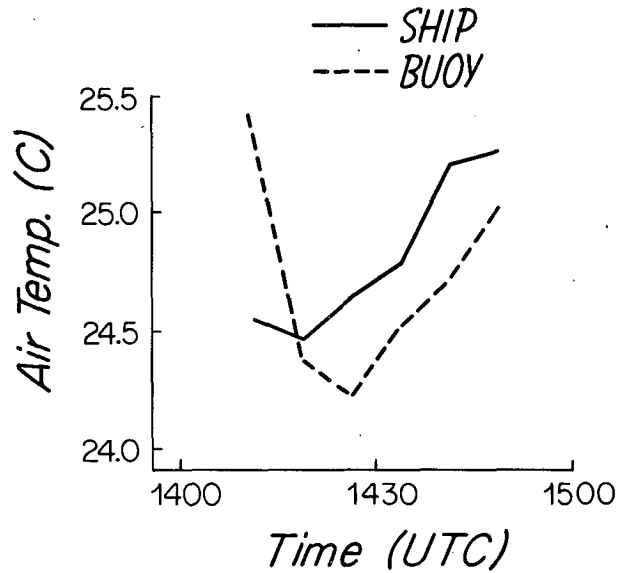


FIG. 12. Air temperature; comparison 9.

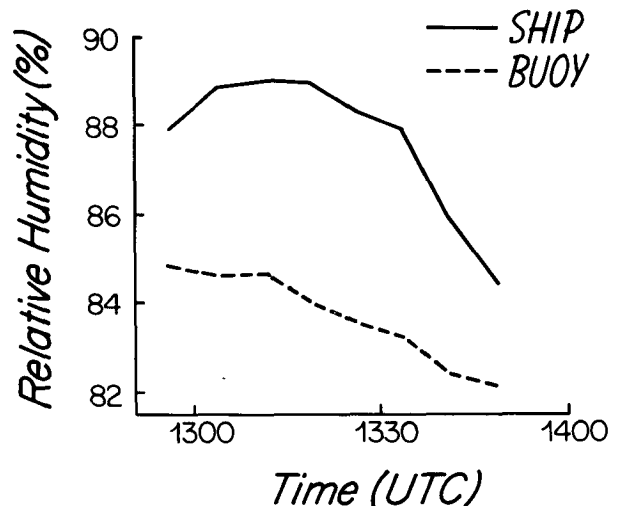


FIG. 13. Relative humidity; comparison 10.

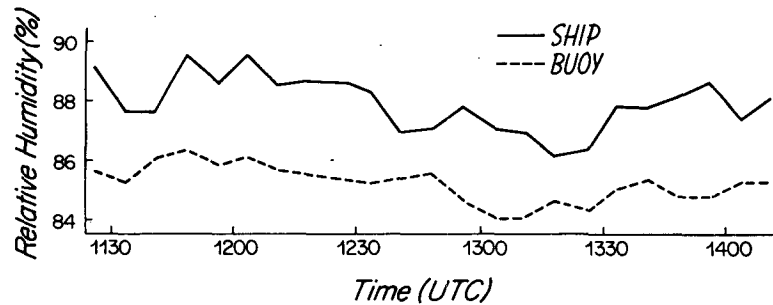


FIG. 14. Relative humidity; comparison 11.

the MR agree with the ship measurements to within the accuracy of the ship measurements. During the day, the MR air temperature measurements can be biased high by 1°C or more.

### c. Relative humidity

There were only three comparisons in which appropriate data were recorded on both ship and buoy. In comparison 7, the ship's dewpoint temperatures were suspect and were rejected. Comparisons 10 and 11, shown in Figs. 13 and 14, show a reasonable correlation between the signals. The mean difference in comparison 11 is 2.7% RH. The uncertainty in relative humidity computed from dewpoint is about  $\pm 2\%$  RH for an uncertainty of  $\pm 0.4^\circ\text{C}$  in dewpoint temperature. Thus, although the amount of data is meager, what there is indicates that the two sensors agree reasonably well.

## 8. System performance

There have been a total of 22 deployments of the MR, all of 6-month nominal duration and most within  $10^\circ$  of the equator in either the Atlantic or Pacific Ocean. The exceptions are five which were moored at about  $28^\circ\text{N}$  in the Atlantic in 1986. During 5 of the 22 deployments, the surface buoy containing the MR either sank or was stolen. There are also four deployments from which no useful data were obtained. There are, then, 13 deployments on which to report performance and failure analysis.

The DDL has failed on three occasions, all due to early-life component failures. The first two WR failures were due to radiation from the ARGOS antenna. We could find no reason for the other three component failures. The only anemometer problem occurred when the manufacturer-installed bearings were left in a new instrument and subsequently corroded. One compass failed when the flexible wires which connect the compass to the connector on the exterior case broke from metal fatigue. Relative humidity sensors were installed in 10 of the 13 recovered MRs. In five of these, they failed, in one case causing a battery drain leading to

failure of the rest of the MR. In four of the other deployments they drifted seriously, leaving only one deployment in which the relative humidity values were recoverable from beginning to end. Air and water temperature thermistors, pyranometers, and barometers experienced no failures during the deployments. Aside from the relative humidity sensors, all components and sensors have worked satisfactorily in 6 of the 13 deployments.

## 9. Summary

A new meteorological sensing, telemetering, and recording package for long-term deployments (6 months) on surface buoys in midocean has been described. The system design is based on digital electronics for flexibility in length of recording interval, number and type of analog and digital sensors, and data storage and telemetering devices. The basic sensor suite was selected to measure the parameters required for computing fluxes of momentum and sensible and latent heats by bulk aerodynamic methods and the flux of shortwave solar radiation into the ocean. Sensors were chosen for accuracy, reliability, and commercial availability and include wind speed and direction, air and sea temperatures, solar radiation, barometric pressure, and relative humidity. All but the relative humidity have been successful. The MR has been used in a total of 22 nominal 6-month deployments.

*Acknowledgments.* Engineering design of the MR and initial assembly language programming of the DDL were by Richard T. Nowak. Programming of the wind processor was by Paul Fucile. John Pomer wrote the final versions of both programs as well as making numerous other improvements in the MR. Jerome Dean and Richard Koehler made valuable suggestions for improvements. The National Science Foundation (NSF) supported the development of the MR and its deployment in SEQUAL through grants OCE 81-22061 and OCE 83-11108. Participation in Tropic Heat was supported by NSF Grant OCE83-10982 and in LOTUS and FASINEX by Office of Naval Research, contracts N00014-76-C-0197, NR 083-400 and N00014-85-C-0001, NR83-004, respectively.

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