Improved Meteorological Measurements from Buoys and Ships for the World Ocean Circulation Experiment

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ABSTRACT

The World Ocean Circulation Experiment (WOCE) is directed at understanding ocean circulation and its interrelation to climate. During WOCE, moored buoys and ships will provide attractive platforms from which to make accurate in-situ measurements of the basic observables-- sea surface temperature, air temperature, wind velocity, barometric pressure, solar and longwave radiation, humidity and precipitation. From these measurements accurate estimates of the air-sea fluxes can be made. Drifting or moored air-sea interaction buoys will also be needed in WOCE for the verification of the surface data collected by remote sensing.

The overall goal of the "Improved Meteorological Measurements from Ships and Buoys" (IMET) effort is to develop accurate and reliable means of making meteorological measurements from ships and buoys during WOCE. Work being done at the University of Southern California concentrates on improving longwave radiation sensors. Scripps Institution of Oceanography is evaluating the effect of platform motions on radiometers, anemometers, and heading sensors. The work at the Woods Hole Oceanographic Institution includes development and evaluation of improved sensors, testing to quantify errors associated with present sensors, development of prototype data loggers capable of supporting intelligent data acquisition algorithms that reduce measurement error, and testing of sensors and data loggers on local moorings and on research ships.

Prototype buoy and ship data loggers are complete. Prototypes of some of the sensor modules are also complete. An optical WORM (Write Once, Read Many times) disc for storage has been working well even during rough weather testing on OCEANUS (Prada,1988) .Test buoy deployments began in January 1989 and test ship installations will be in operation later in 1989. Sensors for all variables are under test on land. Testing of the most promising of these will be continued on the test buoy and ship installations beginning in 1989.

1. Introduction.

Vertical exchange across the air-sea interface of horizontal momentum and of buoyancy, including heat and freshwater, couples the ocean and atmosphere. Observing this coupling is a fundamental need if WOCE is to understand ocean circulation and its interrelation to climate. During WOCE moored buoys and ships will provide especially attractive platforms from which to make accurate in-situ measurements of the basic observables -- sea surface temperature, air temperature, wind velocity, barometric pressure, solar and longwave radiation, humidity and precipitation -- and from which to make accurate estimates of the air-sea fluxes. They are attractive because they provide the means to make a direct measurement in situ and because sensors and electronics are returned periodically for calibration. The pre- and post-calibration procedure, along with an understanding of sensor performance in the field, provide the methodology to maintain and quantify the accuracy of the measurements. To obtain such high quality measurements in support of objectives of the Core 1 (the global description), Core 2 (the Southern Ocean), and Core 3 (ocean process studies) projects, the plan during WOCE is to deploy moored buoys equipped with meteorological instrumentation and to similarly equip a subset of the ships involved in WOCE.

The overall goal of the "Improved Meteorological Measurements from Ships and Buoys" (IMET) effort is to develop accurate and reliable means of making meteorological measurements from ships and buoys during WOCE. Work being done at the University of Southern California concentrates on improving longwave radiation sensors and determining the accuracy of net longwave flux estimates. Scripps Institution of Oceanography is evaluating the effect of platform motion on radiometers, anemometers, and heading sensors and investigating methods of reducing that error. The work at the Woods Hole Oceanographic Institution includes development and evaluation of improved humidity sensors; testing to quantify errors associated with present sensors for precipitation, sea and air temperature, and barometric pressure; participation with Scripps in the work on platform motion effects; development of prototype data loggers capable of supporting intelligent data acquisition algorithms that reduce measurement error; and testing of sensors and data loggers on local moorings and on research ships. Testing will include a variety of sensors (spanning various measurement techniques and a range of costs) in order to be able to quantify the trade-offs between accuracy, reliability, and initial expense.

2. Required measurements.

The basic meteorological quantities that need to be measured include sea surface temperature (SST), air temperature, wind speed and direction, barometric pressure, humidity (which may be obtained through wet bulb depression), incoming solar and longwave radiation, and precipitation. Stress, sensible heat flux, latent heat flux and evaporation are determined from these basic data using bulk formulae. Net shortwave radiation and net longwave radiation are also calculated. Accuracies of 10 watts per square meter are sought in the estimates of the mean values (averaged over monthly and longer time scales) of each of the four components of heat flux (sensible, latent, shortwave, longwave); accuracies of approximately 1 millimeter per day are sought in evaporation and precipitation; and an accuracy of 10% or 0.01 Pa is sought in stress.

Table of Desired Measurements.

Variable	Units	Min	Max	Res
Wind Speed	m/s	0.7	50	0.1
Wind Direction	deg	0	360	0.7
Air Temp.	degC	-40	45	0.001
Sea Surface Temp.	degC	-5	45	0.001
Solar Insolation	W/m2	0	1400	0.1
Barometric Press.	mb	850	1050	0.1
Relative Humidity	%RH	0	120	0.1
Longwave Radiation	W/m2	0	600	0.1
Precipitation	mm/hr	0	600	0.1

The majority of conventional surface meteorological data are provided by observations from the Volunteer Observing Ships (VOS). These data contain random errors due to inadequate sampling, poor instrument calibrations, ship air flow disturbance, etc. Effects such as heat contamination from the ship and salt contamination of wet bulbs result in systematic biases. Random errors can be reduced by averaging but systematic biases must be identified by comparison of the VOS data with higher quality data from meteorological buoys, research ships, or an improved subset of the VOS. Drifting or moored air-sea interaction buoys will also be needed in WOCE for the verification of the surface fluxes of heat and momentum which have been determined from remote sensing or from atmospheric general circulation models and to obtain data from regions away from regular ship tracks. Data at the original sampling rate will be stored in the buoys for later recovery; averaged data will be telemetered via ARGOS for immediate use.

Net short wave radiation is estimated by measuring downwelling short wave radiation with a pyranometer and multiplying by (1-alpha), where alpha is the albedo (as from Payne 1972 for example). Instruments must be carefully calibrated and gimbal mounted to compensate for ship and buoy motion. Downward long wave radiation is measured by a similar sensor fitted with an opaque dome. Errors due to the radiative heating from parts of the ship in the field of view can be large and are additional to error due to motion and sensor deficiencies. Upwelling long-wave radiation must be inferred as the graybody emission of the sea surface plus the reflection of downwelling long wave radiation by the sea surface and by modelling dependence on air temperature and humidity (Siegel and Dickey 1986). Errors in measuring SST will enter in the graybody formula and are thus potentially large, but there are also uncertainties in the sea surface emissivity, sea surface reflectance, and the empirical model dependence on air temperature and humidity. However, it is difficult to make a good measurement of the sea surface temperature of the ocean. With diurnal heating, SST may be up to 3 degrees C warmer than the temperature at a depth of 1 meter; and, during a shower, relatively fresh water can be found at the surface that is cooler than the water below. Further, sensors placed on a ship or buoy hull may be affected by the thermal mass of the hull and, if not shielded, may be directly heated by the penetrating radiation. Such radiative heating is also the primary problem with air temperature measurements although aspirated air temperature sensor shields can be used to attempt to bring the error in air temperature down to approximately 0.2 degrees C. Humidity measurements of the desired accuracy will require the development of new sensors. Errors in the buoyancy flux will be associated with errors in both total heat flux and precipitation estimates.

3. Meteorological instrumentation.

Meteorological packages and sensor sets for use on both ships and buoys during WOCE are now under development. Air-sea fluxes will be computed using stability dependent algorithms for momentum, sensible heat, and latent heat (Large and Pond 1981,1982) and computing net shortwave using an albedo look-up table, and net longwave by estimating outgoing longwave with an improved graybody algorithm now being developed. Raw data and original sampling rate (as fast as every minute for one year) fluxes will be stored: several-hour averaged surface variables and fluxes will be telemetered via ARGOS. ARGOS data will be monitored (and quality checked so it will qualify for distribution via GTS) and archived at an accessible (dial-up and/or Ethernet) data base.

Prototype buoy and ship data loggers are complete. Prototypes of some of the sensor modules are also complete. An optical WORM (Write Once, Read Many times) disc for storage has been working well even during rough weather in a test installation on OCEANUS (Prada and Baggeroer 1988). Test buoy deployments began in January 1989, and test ship installations will be in operation later in 1989. Sensors for all variables, including precipitation, are under test on land. Testing of the most promising of these will be continued on the test buoy and ship installations beginning in 1989. Special efforts are being made to develop relative humidity and precipitation sensors, to reduce errors in sea surface and air temperatures, to reduce errors in short and longwave radiation measurements associated with platform motion, to develop an improved wind /vane/ compass sensor, and to establish a reliable system configuration for use on ships and buoys.

4. Shipboard system.

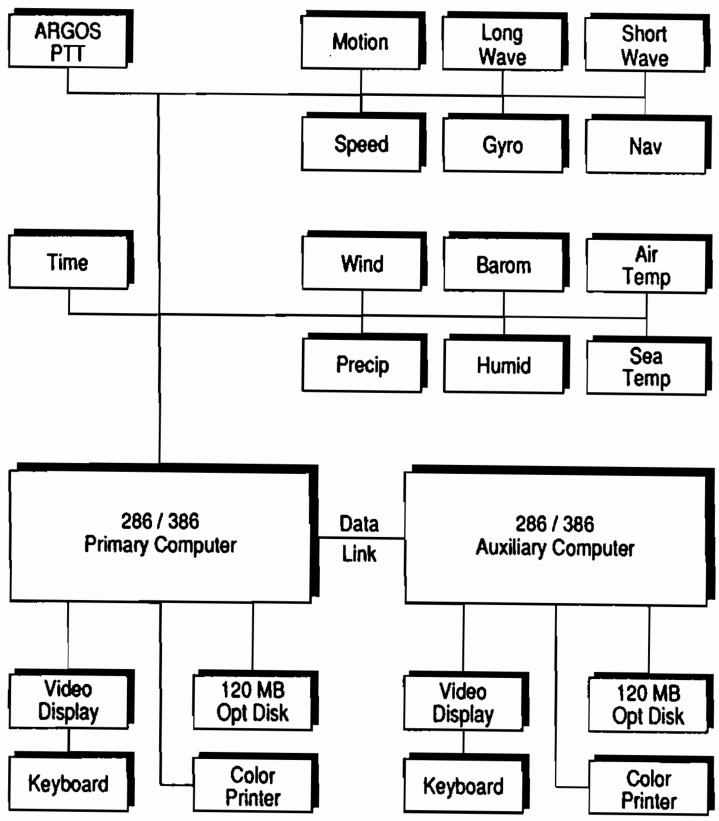

FIG.1. Shipboard system block diagram

The ship data logger/controller is an NEC APC-IV personal computer, as shown in Figure 1. Software development is carried out using standard MS-DOS compatible programs. The primary computer collects the data from the various sensors via a digital interface built into each sensor. It then stores the raw data on the optical disk, displays the data on a real time operator display, performs calculations and transmits longer term average data and calculated data via ARGOS. There is a color printer for hard copy data in a strip chart form and a keyboard for operator interaction. There are two basic sensor groupings, one that collects one minute averages and one that is capable of high speed sampling of motion and radiation if desired. There is an auxiliary computer that is capable of accessing the primary optical disk and doing data analysis and evaluation without disturbing the primary data collection.

5. Buoy system.

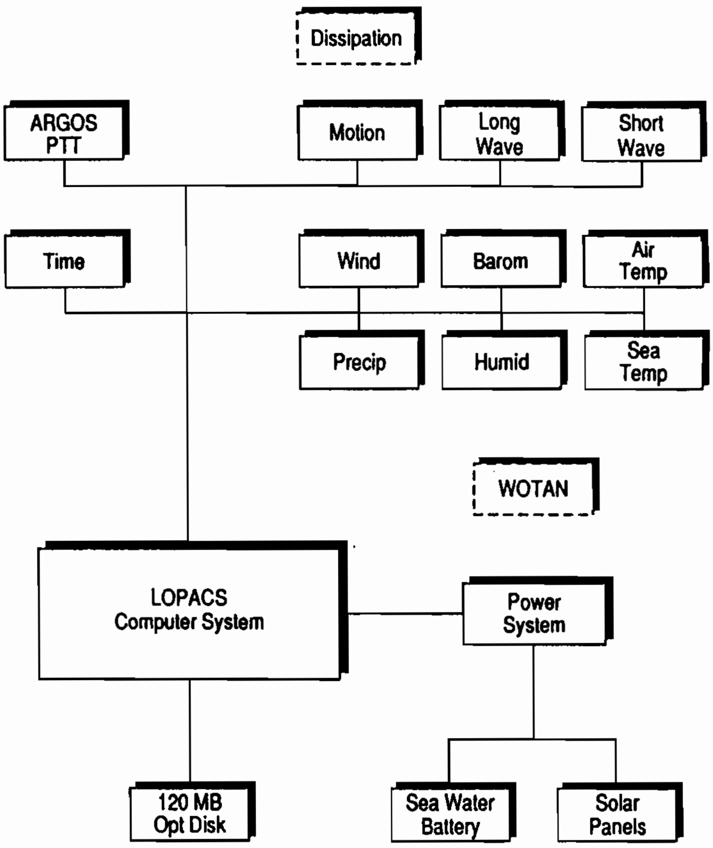

FIG.2. Buoy system block diagram

The buoy data logger/controller is based on a low-powered processor unit called LOPACS as shown in Figure 2. This controller is a CMOS based, IBM compatible, commercially available unit that is described in Reference 6. The software development is carried out using standard MS-DOS compatible programs that would be similar but not the same as the ship system. The system functions in the same way as a ship system except there is no operator display or interaction. The electronics is housed in a watertight area on the buoy and can be controlled via a watertight connector to a remote terminal.

6. Sensor modules.

The sensor set will provide measurement of wind velocity, air temperature, sea temperature, barometric pressure, relative humidity, incoming shortwave radiation, incoming longwave radiation and precipitation. Various alternate sensors for each variable are being tested to establish reliabililty, accuracy, and cost versus performance information for each type of measurement. The sensor modules being designed and built to work with the system are the current choice for sensors to satisfy the measurements required and are referred to as the "strawman" sensor set. The following figures and paragraphs describe the strawman sensor configurations.

Each sensor will be mated to a microprocessor based module that will perform some sampling tasks, convert the raw sensor output to engineering units, and send the data digitally over RS-485 (ship) or RS-232 (CMOS open drain) (buoy) link to the data logger/controller. Refer to Figure 3. for the configuration of the Digital Data Module. Each digital module is housed in a plastic, watertight 4.5" diameter housing with a 4 wire underwater connector providing power and data. In the development modules, there are two aluminum chassis, one of which contains one or more custom front end interface printed circuit cards while the other contains at least three cards, including a power and communications board, a digital module processor (DMP) card (currently a Basicon 2i unit) and an integrating 15 bit plus sign, analog to digital converter,parallel and counter I/O card. The (DMP) is typically programmed in BASIC 52 with 'C' as an alternative. This modular approach permits development of future sensor modules by investigators in other laboratories that will be compatible with the data collection system.

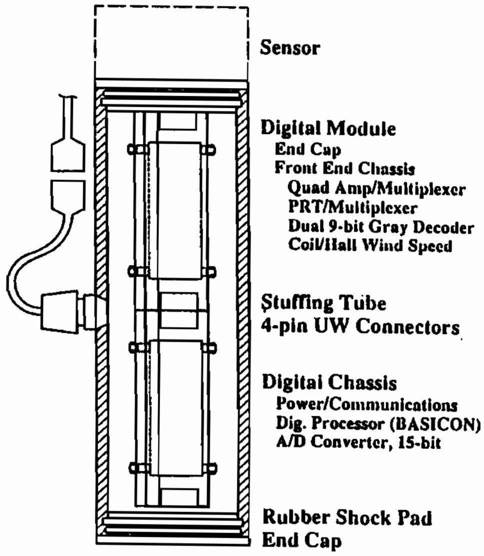

FIG.3. Digital data module

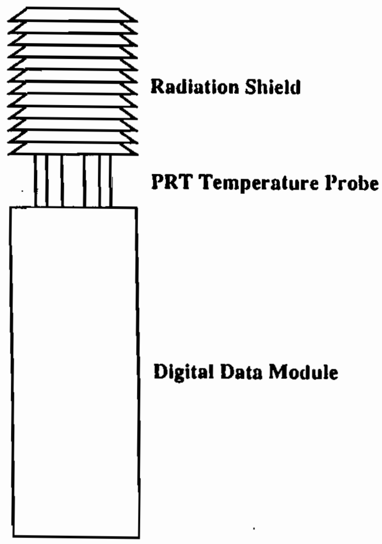

FIG.4. Air temperature module

The air temperature module uses a PRT (Platinum Resistance Thermometer) inside of an R. M. Young radiation shield shown in Figure 4. An autoranging, ratiometric measurement will be made to provide as high an accuracy as possible. The PRT offers a linear, ultra low drift sensor. Close coupling of the sensor and the shielded front end electronics will provide a stable, low noise analog section and the DMP will be programmed to provide corrections based on stored calibration data.

Sea Surface Temperature is electronically very similar to the Air Temperature module but will be housed in an aluminum underwater housing for mounting under the buoy and is shown in Figure 5. The ship mounting is being evaluated but will probably be custom for each ship that the system is installed on.

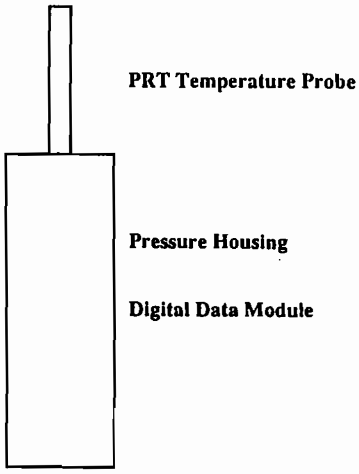

FIG.5. Sea surface temperature module

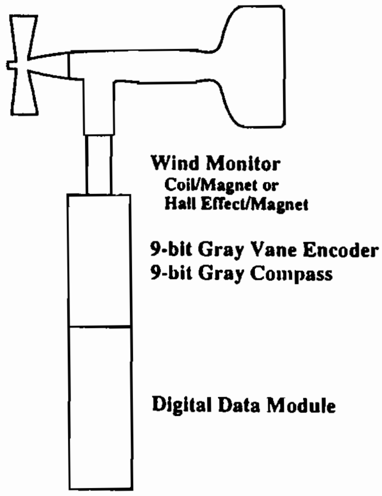

FIG.6. Wind speed and direction module

The wind speed and direction module is shown in Figure 6. An R. M. Young Wind Monitor has been selected since it has a proven record and uses a propeller to measure speed. The potentiometer is removed and the vane shaft extended down into the top of the data module housing addition. A commercially available 9 bit Gray Code shaft encoder is coupled to the vane. A Digicourse Model 226 gimbaled compass with a 9 bit Gray Code output is in the same housing . The wind speed will be measured with either the standard coil and magnet or with a Hall Effect unit and magnet. The front end electronics include a dual 9 bit Gray code to binary decoder and electronics to process either of the speed signals. The DMP will be programmed to sample, store and process the standard vector averaged wind data over a one minute time period.

The Short Wave Radiation module will consist of an Eppley PSP (Precision Spectral Pyranometer) mounted on an aluminum housing which provides a reference mass for the PSP. This is fastened to a standard digital module and the combination is mounted in a 2 axis gimbal as shown in Figure 7. This gimbal has low corrosion, sealed bearings that are filled with a lubricant. This provides extended life and some damping. The sensor can be adjusted in the gimbal to minimize acceleration sensitivity. The low level signal from the sensor is amplified by a low noise amplifier and sampled by the A/D card under DMP control.

Long Wave Radiation is measured by a Foot thermopile (Foot 1986) and has two compensating thermistors. The low level signals are amplified, multiplexed and stored by the DMP, where the compensation is accomplished by software rather than analog electronics. The long wave sensor also has a two axis gimbal as shown in Figure 8.

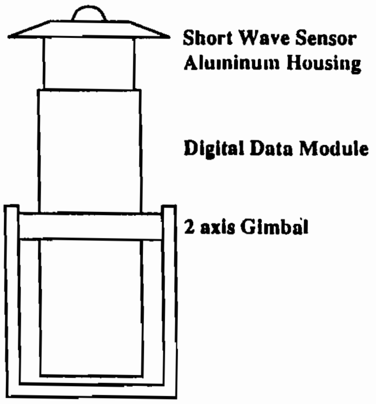

FIG.7. Short wave radiation module

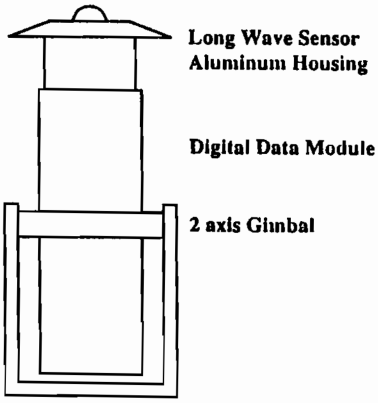

FIG.8. Long wave radiation module

The Barometric Pressure and Relative Humidity module shown in Figure 9 uses a common digital data module. The barometric pressure gage is an AIR (Atmospheric Instrumentation Research Inc.) Model DB-1A with a parallel digital output that goes directly to the DMP. The relative humidity unit is a Rotronics Model MP-100-F that has analog outputs for both relative humidity and local temperature. These are multiplexed into the A/D card and controlled by the DMP.

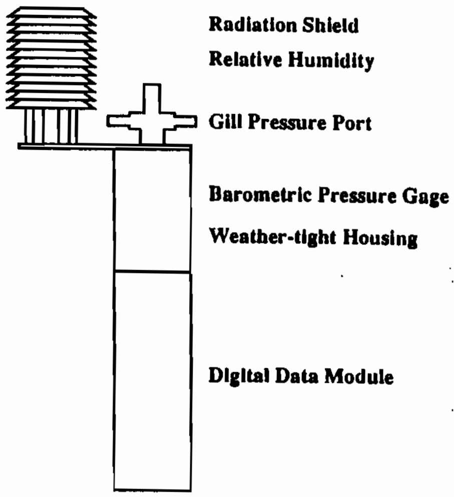

FIG.9. Barometric pressure and relative humidity module

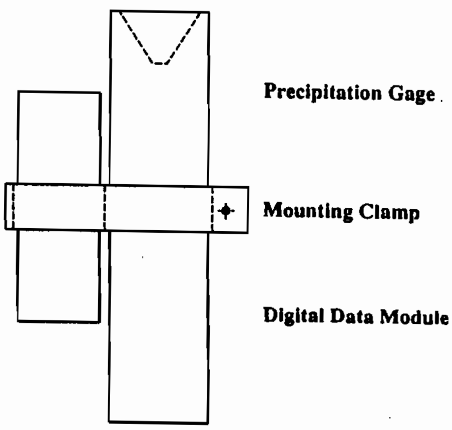

FIG.10. Precipitation module

The Precipitation sensor is an R. M. Young Model 50102 Rain Gage with a 0 to 50 millimeter capacity unit that automatically empties and repeats the measurement and is shown in Figure 10. The unit has a 0 to 5 volt output that is converted in the A/D board. The DMP makes measurements and keeps track of the emptying cycles. There is a heater for cold weather use but this would only be used on ships for power reasons. The digital data module will be mounted beside the rain gage.

7. Deployments during WOCE.

Potential deployments of the IMET systems in moored arrays and on ships in WOCE are discussed below. The primary goal of these deployments would be to provide data needed for the validation of the air-sea flux and meteorological data fields to be produced during WOCE. Detailed reasons for the deployments are given elsewhere; but briefly, these deployments would:

- Provide, at the site of a moored array embedded in a Core 3 or Core 1 or 2 data field, a point with time series of the surface variables and air-sea fluxes of the highest possible accuracy, both for examining response to local forcing and for reducing the error in the larger scale field.
- Validate routine products of atmospheric models, serving as a diagnostic point to check the performance of coupled atmosphere-ocean models.
- Provide very accurate input data or provide a means to validate/estimate the error in the air-sea flux fields used to force ocean or atmosphere models.
- Provide, at selected sites, accurate time series of surface variables and air-sea fluxes to assess the accuracy of existing climatologies (such as the Levitus data) and, if not assimilated, of the data fields being produced during WOCE.
- Validate satellite products and methodology, including wind, SST, rainfall (during the Tropical Rainfall Measurement Mission, TRMM), the use of microwave radiometers (SSM/I) to measure total water content in the atmospheric column and infer surface humidity, and radiation products from polar orbiting satellites.
- Provide the means to assess systematic errors in the data fields collected by the Volunteer Observing Ships (VOS).
- Lay the groundwork for a methodology and network of moored buoys that will replace the weather ships and for a method of maintaining a near real-time watch on oceanic locations where good surface data would, because of teleconnections, be a diagnostic to change in global circulation/climate.

<u>Moored Buoy</u>

The buoy deployments would be as follows:

- 1991-1993: Eight moored surface buoys, in the Ekman/Subduction process study in the Azores-Canary area.
- 1993-1997: Up to ten moorings at special locations and in arrays with a minimum of 3 elements for the purpose of calibration and validation of the WOCE air-sea flux fields. These arrays would be maintained at their sites for two years.

The large scale air-sea flux fields that might be provided by satellites and models will not be sufficient to address the needs of the planned Ekman Subduction experiment in the eastern North Atlantic in 1991 -1993. Accurate, in situ measurements are needed to provide the most accurate estimates of the wind stress and buoyancy forcing of the upper ocean. An array of eight surface moorings, each with meteorological instrumentation and each supporting current meters is under discussion.

For WOCE the plan is to build 10 surface meteorological mooring hardware sets by 1993 and thus to be able to maintain (with back to back one year deployments equipment at 2-3 sites in any year. Coordination will be sought with other investigators to add current meters to each mooring to examine local ocean response to atmospheric forcing, to quantify the division between geostrophic and ageostrophic wind-driven flows, and to add data points with details of the vertical structure to the fields of ocean circulation being constructed during WOCE.

Ship Deployments

The ship deployments would be of three types:

- Research Ship System (RSS): Research Vessels participating in the WOCE Core 1, 2, and Core 3 activities with science parties seeking high quality meteorological observations.
- WOCE Hydrographic Program Ship System (WHPSS): Research Vessels participating on the WOCE Hydrographic Program.
- Ship of Opportunity System (SOS): Volunteer Observing hips (VOS) making repeated XBT and/or ADCP sections.

The RSS installation on U.S.Research Vessels would include three sensor installations (port, starboard, and bow mast) and a sensor suite designed to provide the best possible measurements of the surface variables and best possible estimates of the air-sea fluxes at reasonable cost (thus excluding as standard items an infrared hygrometer, optical rain gauge, and sonic anemometer). Two NEC APC-IV's would be used to provide redundancy and real-time access for the science party to the meteorological data. One APC-IV would carry on ARGOS telemetry and data logging at the standard rate and in the format to be provided by the other ships and buoys; the second APC-IV would be menu-driven and available to the science party and/or resident technician. This underway sampling would be coordinated with other underway sampling efforts. The optical disks would be returned after one or more legs to be quality-checked and read into the data base. Five RSS would be built in order to maintain four at sea. Targeted are the research ships where collection of meteorological data will be of direct scientific interest. Also, it is planned that one RSS be installed temporarily on a U.K. ship involved in WOCE for purposes of intercomparison. It is hoped that the five RSS will remain in operation following WOCE and that their data will continue to be distributed via GTS and archived.

The research ships involved in the WHP are the second focus of attention because they will provide platforms that will provide ship velocity data (via GPS), permitting true wind to be determined, and because the installation of a semi-permanent meteorological package (WHPSS) would benefit from the attention of the resident technician/science party on board. Port and starboard installation would be done and a single APC-IV would be installed. This would support ARGOS telemetry of several-hour averaged surface variables and fluxes, recording of raw data and raw sampling rate fluxes on optical disk, and simple strip-chart display (on video terminal and/or printer) of the data. Prime candidates are those ships in the WHP making sections in data sparse regions and/or sections that pass thru regions in particular need of calibration/validation.

The VOS making the repeat XBT sections would be the third choice. This SOS package will be a self-contained , unit similar to the package used on buoys. A single sensor set will be installed on a temporary mast. When possible, one sensor module will be used to link to ship's navigation, permitting determination of absolute wind and momentum flux. Internal logging on optical disk of raw data and raw sampling rate fluxes and ARGOS telemetry of several-hour averaged data will be supported. Primary targets for the planned installations will be ships equipped for WOCE to collect XBT and/or ADCP data, especially those transiting regions with otherwise sparse coverage of surface meteorology and air-sea fluxes and/or locations where the modelling and remote sensing efforts need validation data. Four SOS will be built and used in a cooperative effort involving the investigators collecting the XBT/ADCP data.

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