TOGA-TAO: A Moored Array for Real-time Measurements in the Tropical Pacific Ocean

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Abstract

The importance of the El Niño-Southern Oscillation phenomenon in year-to-year fluctuations of the global climate has led to efforts to improve the real-time ocean observing system in the tropical Pacific. One element of this improved system is the TOGA-TAO (Tropical Atmosphere-Ocean) Array of wind and upper ocean thermistor chain moorings. This array, the result of an international effort, has already provided the rudiments of a basin-wide, real-time observing system and plans call for a major enhancement during the second half of the TOGA decade. The development of the TAO array is discussed, recent results from the pilot measurements are described, and plans for the expanded array are presented.

1. Introduction

Recognition of the global climatic influence of El Niño Southern Oscillation variability has led to an increased need for real-time diagnosis of the current state of the tropical Pacific and forecasts of its likely evolution. Description and model simulation of the tropical ocean requires knowledge of the basin-wide atmospheric forcing and the ocean's response. To obtain these fields in real-time the Tropical Ocean-Global Atmosphere (TOGA) Program has initiated an improved tropical Pacific Ocean observing system. One element of this system is the Tropical Atmosphere Ocean (TAO) Array of wind and upper ocean thermistor chain moorings. In this note the rationale for the TAO Array is reviewed, some initial results from the pilot array are discussed, and plans for the full TAO Array during the second half of TOGA are outlined.

At the outset of the TOGA Program, it was determined that basin-wide measurements of key oceanic and atmospheric parameters in the tropical Pacific were required in order to characterize the low frequency (seasonal to interannual) variability of the coupled system and to validate models of these phenomena (National Research Council 1983). The concept of a "thin monitoring" network was developed which included observations of surface wind stress, SST, upper ocean thermohaline structure, surface heat fluxes, and equatorial circulation. This network was synthesized out of the existing measurements which had been initiated as part of several previous or ongoing tropical Pacific research programs (North Pacific Experiment [NORPAX], Pacific Equatorial Ocean Dynamics [PEQUOD], and Equatorial Pacific Ocean Climate Studies [EPOCS]).The TOGA monitoring network included expansion of the island sea level, ship of opportunity XBT, and surface drifter programs and increased use of the satellite products, particularly for SST.

Initial TOGA planning recognized that the existing capabilities, even when expanded with available resources, would be inadequate to provide the quantitative description required. Ship of opportunity XBT sampling would remain deficient in regions remote from ship tracks and in regimes with large high frequency variance (e.g., see Fig. 3 in Pazan and White 1987). Accurate wind fields are even more difficult to obtain. Halpern (1988) estimated that monthly mean wind speed on the equator requires at least 10 observations per month to achieve an accuracy of 1.0ms^{-1}. However, in vast regions of the equatorial Pacific there are less than five ship observations each month and only along major ship tracks are there more than ten monthly wind measurements (Goldenberg and O'Brien 1981; Reynolds et al. 1989). Even in areas with several ship measurements per month, wind events associated with the intraseasonal atmospheric variation cannot be resolved. Recent studies suggest that such variability may be important in El Nino development (Lau and Shen 1988).

2. The ATLAS system

In order to improve measurements of the tropical ocean thermal structure and surface wind field, the Pacific Marine Environmental Laboratory (PMEL) of

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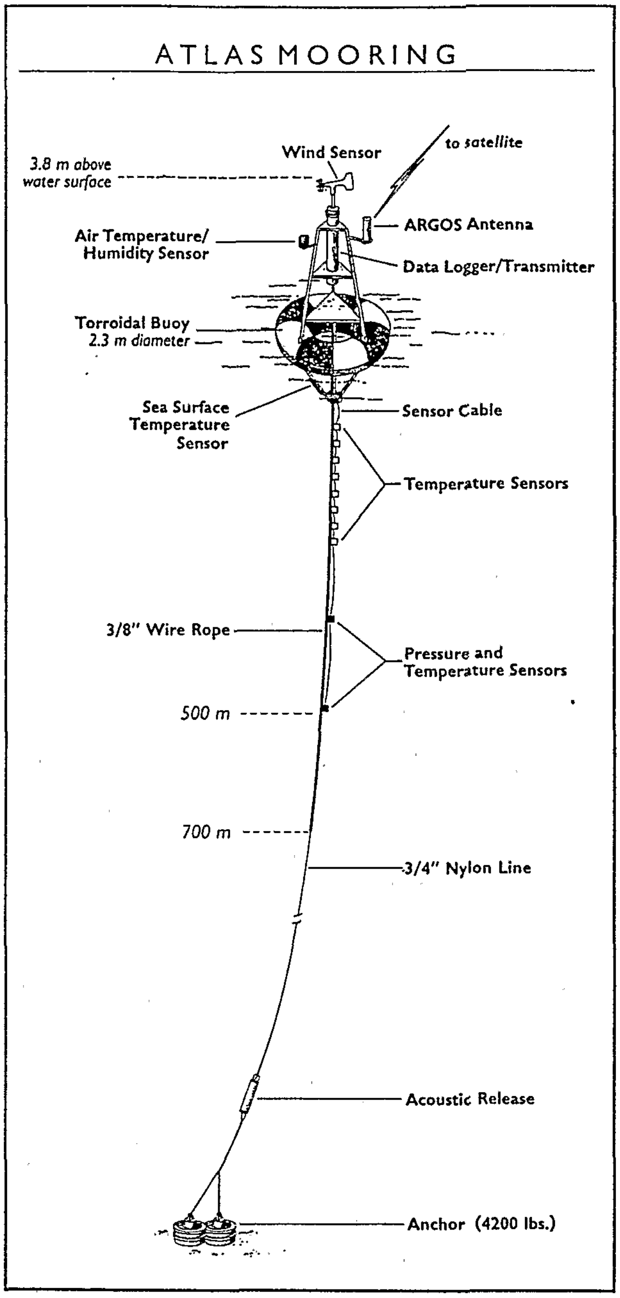

Fig. 1. Schematic diagram of ATLAS wind and thermistor chain mooring. These systems are deployed in the deep ocean in water up to 6000-m deep.

the National Oceanic and Atmospheric Administration (NOAA) began development in 1984 of an inexpensive mooring system called ATLAS (Autonomous Temperature Line Acquisition System; Milburn and McLain 1986). This system (Fig. 1) measures surface wind, air temperature, SST, ten subsurface temperatures to a maximum depth of 500 m, and two subsurface pressures. All data are telemetered to shore via the ARGOS system on NOAA polar-orbiting satellites and recorded internally on magnetic tape cassette or solid state electronic memory. The ATLAS mooring system is based on the design used in the PMEL tropical current meter array (Halpern 1987); it is a taut wire surface mooring with a toroidal float. These moorings can be deployed in water depths of up to 6000 m and remain in place for up to one year.

ATLAS winds are measured at an elevation of 3.8 m using an R.M. Young propeller-vane sensor which is sampled at 2 Hz and vector averaged. Air temperature is measured with a resolution of 0.04°C by a linearized thermistor mounted in a baffled housing to reduce the effects of solar heating. SST is measured at 1-m depth to a resolution of 0.002°C. The thermistor chain consists of polyurethane jacketed double armored three conductor cable. The armoring provides protection against fish bite. At each thermistor pod, the resistance is measured and converted to a frequency which is telemetered to the surface using time multiplexing. Pressure at two locations (300 m and 500 m) on the thermistor chain are also measured in order to sense mooring motions and allow corrections to be applied to the depth of the temperature measurements. Nominal thermistor depths for the ATLAS currently in place are adjusted for eastern (20, 40, 60, 80, 100, 120, 140, 180, 300, and 500 m) and western (25, 50, 75, 100, 125, 150, 200, 250, 300, and 500 m) equatorial Pacific stratification.

The averaging scheme on ATLAS moorings has evolved with the system. Winds are vector averaged and currently most systems telemeter four 6-h averages during each ARGOS transmission. Temperatures and pressures are averaged over 24 h and these values are transmitted. The averaging scheme is somewhat flexible and a standard format is being developed (see Section 4) which will permit hourly synoptic sampling of surface parameters (e.g., wind, air temperature, and SST) and also diurnal averages.

The data stream of the ATLAS system is shown schematically in Fig. 2. Before and after deployment all sensors are calibrated. The predeployment calibrations are applied to all data received via satellite. These data are processed by Service ARGOS and put on the Global Telecommunication System (GTS) for distribution to the operational centers. The data are also forwarded directly from ARGOS to PMEL where they are quality controlled and archived. After recovery and recalibration of the sensors, the data files from each ATLAS are edited, corrected if necessary, and, if possible, gaps are filled with data from the onboard backup recording system. These final data files are submitted to the National Oceanographic Data Center (NODC) and the National Climate Data Center (NCDC) for archival. They are also provided to the TOGA data centers.

3. The present TAO array

At present 19 ATLAS moorings are deployed in the equatorial Pacific Ocean (cover figure). Specific loca-

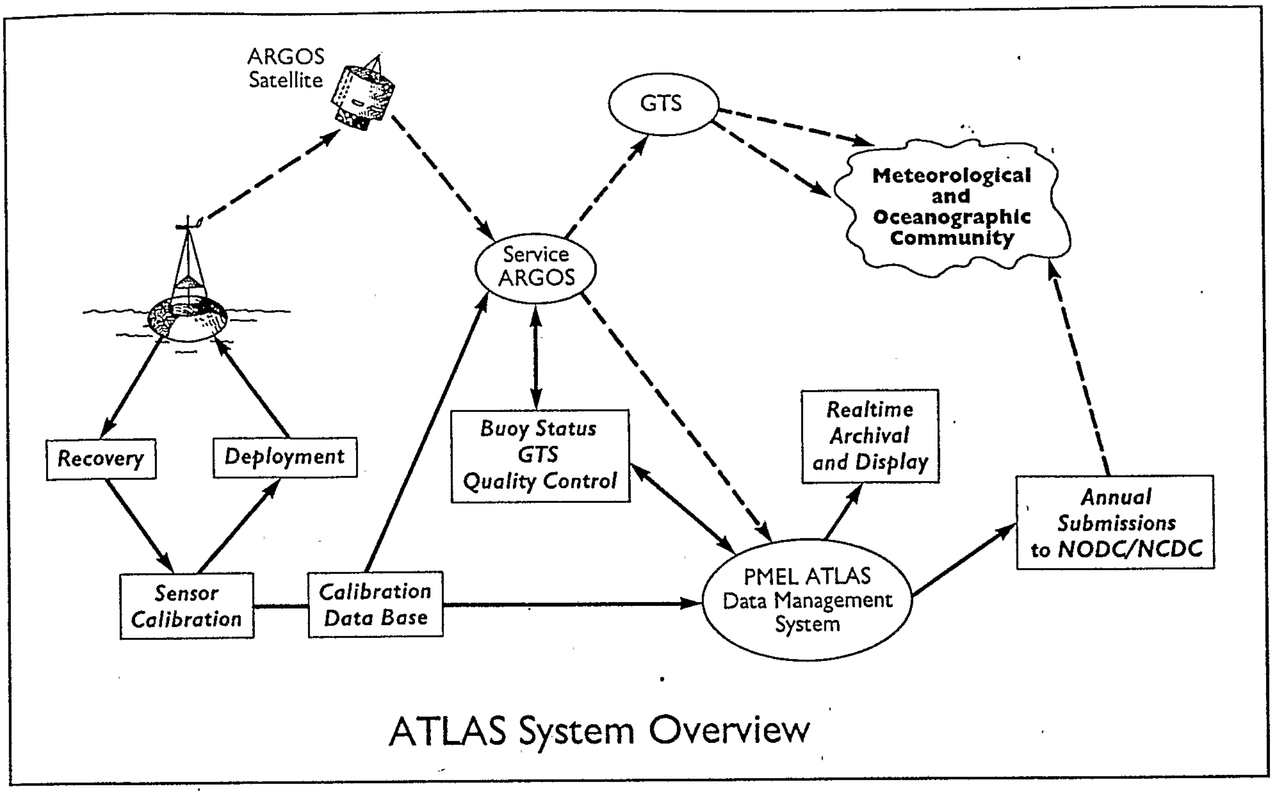

FIG. 2. Overview of the real-time data telemetry and archival for ATLAS moorings.

tions of ATLAS moorings are listed in Table 1. This array developed out of the international TOGA plans for monitoring and process studies. It has been designed in conjunction with the moored current measurement array and these moorings supplement the ATLAS thermal and surface wind field measurements. Along the equator, the combined TAO and moored current meter array samples the zonal variations on broad spacial scales with measurements in the eastern (110°W and 125°W), central (140°W and 170°W), and western Pacific (165°E and 147°E). Off the equator, thermal structure and wind variations in the South Equatorial Current (SEC) are monitored at 110°W, 140°W, 165°E, and 147°E. The North Equatorial Countercurrent (NECC) is spanned at 140°W and 165°E. Measurements at the former longitude are part of a process study to investigate the dynamics of the NECC and include ATLAS along 7°N (147°30°W and 132°30°W) and a current meter mooring at 7°N, 140°W. The basin wide TAO array is maintained through cooperation of scientists and funding agencies in France, Japan, and the U.S.A.

Examples of the recent data from the array are shown by the insets in the cover figure. All data are daily averaged values.

The data inset at 0°, 170°W shows predominantly easterly winds from October through December. These winds were interrupted by westerly wind anomalies in January and February which accompanied the unusual convective activity in the central Pacific in early 1990 (Kousky 1990). Further to the west, near equatorial westerly wind events had begun to occur in November 1989 at 165°E and continued through

TABLE 1. Locations of currently deployed ATLAS moorings.These sites have been maintained since installation; however, data gaps exist becasue of instrument failure.

Location	Installation Date
110°W, 5°N	November 1985
110°W, 2°N	May 1985
110°W, 2°S	December 1984
110°W, 5°S	June 1985
125°W, 0°	May 1987
132.5°W, 7°N	December 1988
140°W, 9°N	May 1988
140°W, 5°N	May 1986
140°W, 2°N	October 1986
140°W, 2°S	June 1986
147.5°W, 7°	November 1988
170°W, 0°	May 1988
165°E, 8°N	July 1989
165°E, 5°N	February 1988
165°E, 2°N	July 1985
165°E, 2°S	July 1985
165°E, 5°S	January 1987
147°E, 2°N	February 1990
147°E, 5°N	February 1990

February. This activity and the associated extension of SST warmer than 28°C into the region east of the date line contributed to the decision by the Climate Analysis Center (CAC) of the National Meteorological Center to issue an El Nino Oscillation (ENSO) Advisory in February 1990. The ocean's response to the westerly winds is evidenced by the thermocline deepening at 170°W in November and December. From the last week of October until the middle of December, the 20°C isotherm (used here as an indication of thermocline depth) dropped 50 m. During this period local winds at 170°W were near normal and most of this thermocline change appears to be remotely forced. Subsequently, the thermocline rose about 25 m and then dropped again in February as the local winds became westerly. The thermocline returned to near normal levels in March-April 1990.

The time series at 2°N, 110°W shows the remote response to these westerly winds as well as a variety of other signals, including the seasonal evolution of the wind and thermal structure in the eastern Pacific. The meridional wind component at 2°N weakened in January-February 1990 as the ITCZ moved southward in its normal seasonal progression. During this period SST warmed by about 4°C from December to March. As shown SST was colder than climatology in December but rose to the climatological value in February, and was about 1°C warmer than normal in April 1990. During the cold period (July-December 1989) the monthly SST and thermocline depth fluctuations associated with the tropical instability waves (Legeckis 1977; Philander 1978) were apparent. SST fluctuations of 2-3°C were common as the near equatorial SST front was advected meridionally by these waves.The movements of this SST front yield the largest amplitude SST change near 2°N (see Fig. 3); however, thermocline fluctuations associated with the instability waves extend to at least 7°N. Due to the meridional distribution of the zonal ocean currents, these waves are much weaker south of the equator (Philander et al. 1985). Effects of the tropical instability waves on surface winds are discussed below

In mid-January 1990 the thermocline depth at 2°N, 110°W reached a local maximum even though local winds remained easterly. This downwelling event can be traced back to the signals at 170°W using the other near equatorial ATLAS time series. The propagation time from 170°W to 110°W is about one month which corresponds to a phase speed of 2.6 m s^{-1}. This speed is approximately the speed of a first baroclinic mode equatorial Kelvin wave and has been observed in numerous studies of such signals in the equatorial Pacific (Ripa and Hayes 1981; Knox and Halpern 1982).

The evolution of the equatorial Pacific wind and SST fields have continued to be monitored and reported in the CAC *Climate Diagnostic Bulletin* (Kousky 1990). The most recent CAC ENSO Advisory (10

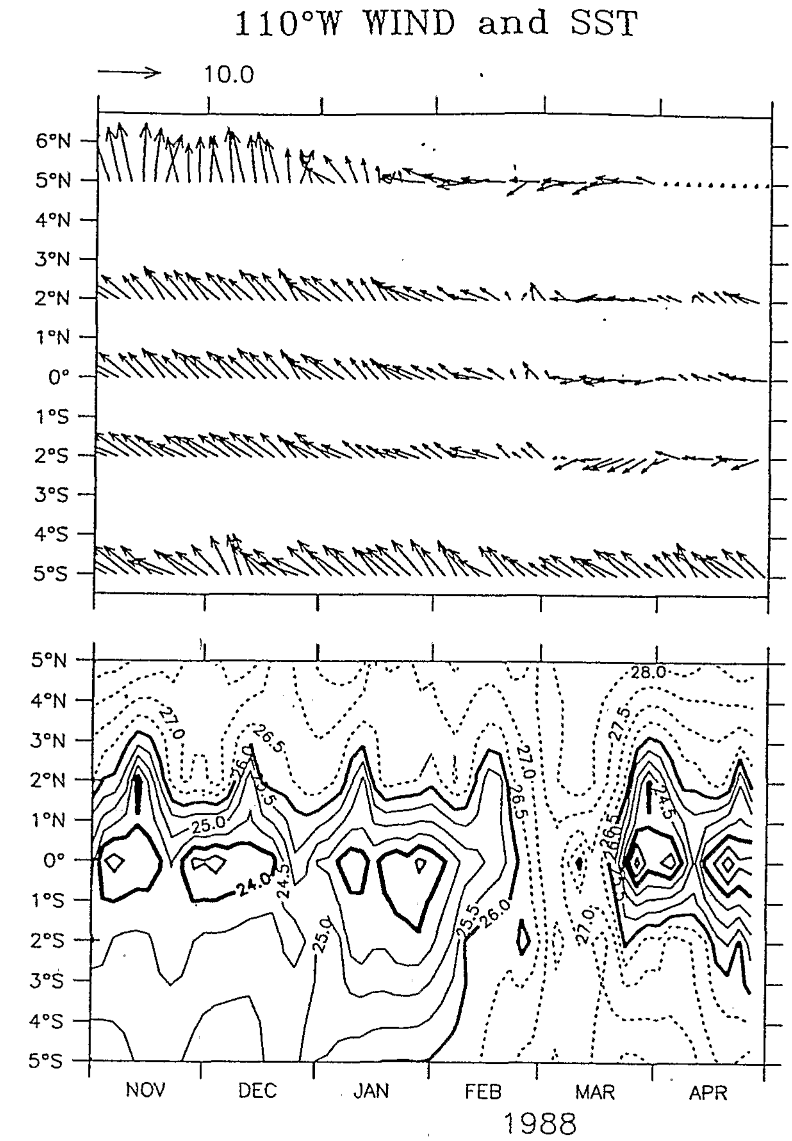

FIG. 3. Wind vectors and sea surface temperature distributions from the ATLAS moorings along 110°W from November 1987 to April 1988. Vectors point in the direction towards which the winds are blowing. The 5°N wind measurements stopped working in April. The SST contour interval is 0.5°C.

September 1990) noted that the warm pool in the western Pacific has continued to expand and that in August 1990, surface water warmer than 28°C extended to 160°W. The boreal fall months are particularly critical in the evolution of large scale tropical Pacific SST anomalies. In this season, convection weakens over Southeast Asia and shifts towards the equator. The warm SST anomalies in the western Pacific in 1990 may lead to enhanced convection and low-level westerly wind anomalies which could precipitate a further eastward expansion of the warm SST. Tropical Pacific conditions will continue to be closely monitored.

In addition to real-time diagnostics, data from the present ATLAS array have also contributed to several recent studies which address a variety of problems including evaluation of model surface wind fields (Reynolds et al. 1989), verification of real-time tropical Pacific Ocean simulations using an ocean General Circulation Model (GCM) (Hayes et al. 1989b), geostrophy near the equator (Picaut et al. 1989), and descriptions of the 1986-87 ENSO warm event (McPhaden et al. 1990; McPhaden and Hayes 1990a).

Hayes et al. (1989c) used TAO data to investigate the influence of SST variations on surface wind in the eastern equatorial Pacific. The tropical instability waves, which are seen clearly in the SST field at 110°W (cover and Fig. 3), result from a barotropic instability associated with the strong meridional shears of the zonal currents (Philander 1978). These waves are not directly forced by the local wind field, so they provide an interesting probe of the response of these winds to changes in SST. Hayes et al. (1989c) found that the divergence of the surface wind near the equator was directly related to the meridional SST gradient. Based on regression analysis (Fig. 4), a

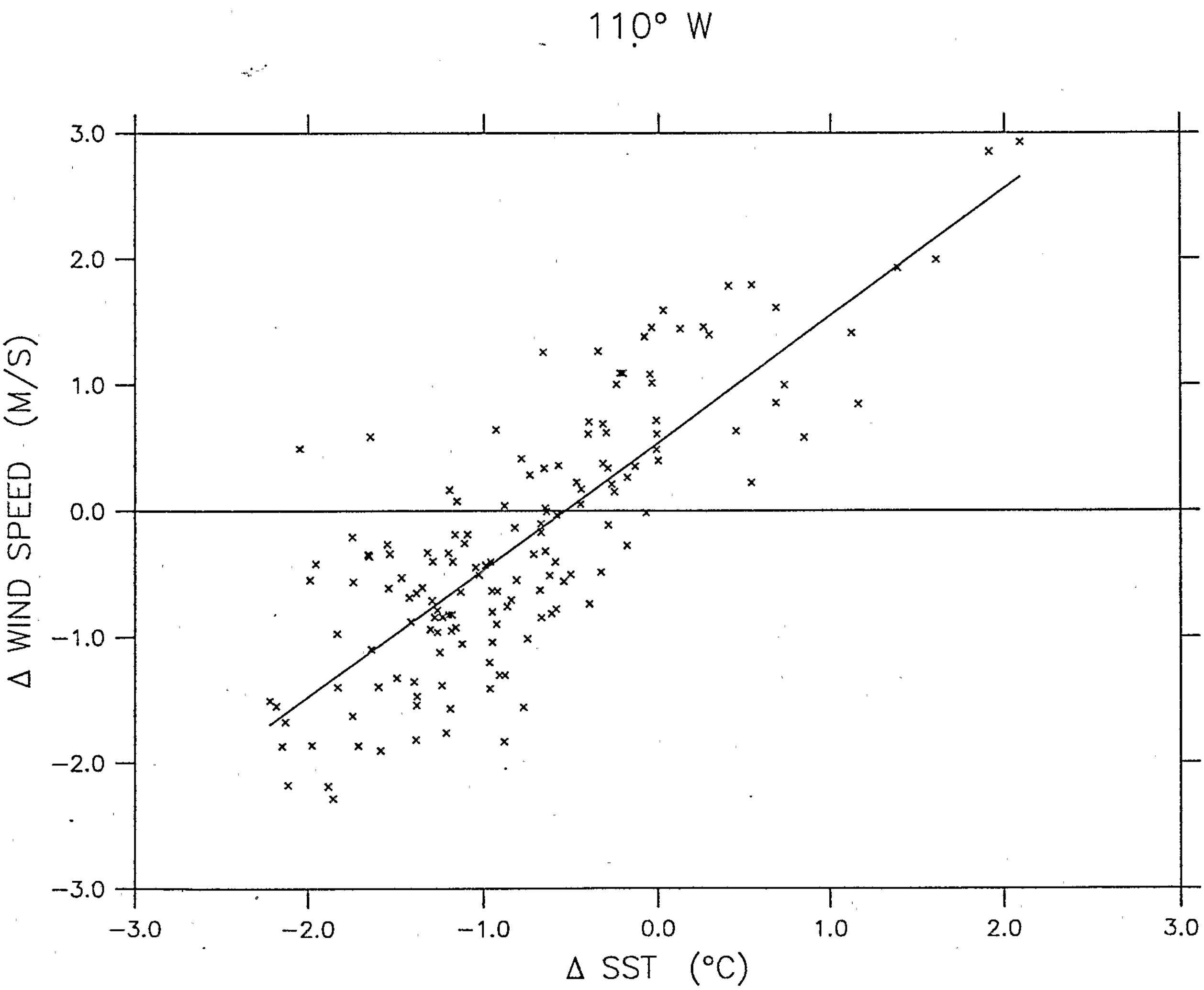

Fig. 4. Scatter plot of the change in wind speed along 110°W between the equator and 2°S (ΔS) vs. the change in temperature (ΔT) between these two latitudes for daily average measurements from July to November 1988. The correlation coefficient between these variables is 0.63.

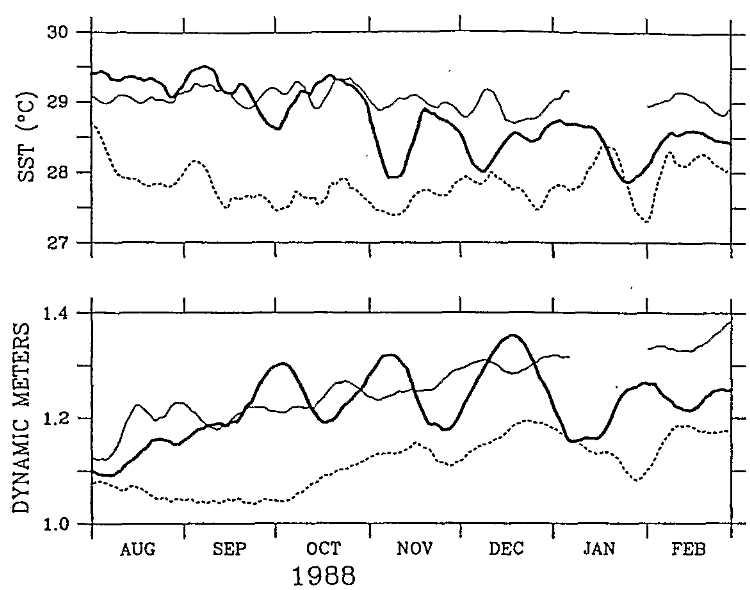

FIG. 5. Sea surface temperature and surface relative to 300-db dynamic height time series from moored temperature measurements at 5°N (heavy solid), 0° (dashed) and 5°S (thin solid) along 165°E. The dynamic height was estimated from the measured temperature profile assuming a constant temperature-salinity relation. Note the prominent monthly oscillations in the surface elevation at 5°N but not at other locations.

temperature change of 1°C between the equator and 2°N led to a change in wind speed of about 1 m s^{-1}. This result supports the hypothesis of Wallace et al. (1989) who suggested that reduced atmospheric boundary layer stability when cool air blows across warm SST decreases the boundary layer shear and increases surface wind speeds by more efficiently transferring momentum from the low level winds to the surface. Wallace et al. (1989) found that this effect is important during ENSO fluctuations. Hayes et al. (1989c) show that the same process occurs on weekly to monthly time scales. Higher winds over the warm water will contribute to enhanced latent heat flux from the ocean to the atmosphere and may be important in the net heat budget in the eastern tropical Pacific.

Recent studies by Takeuchi et al. (1990) have shown that the tropical instability waves also occur in the western Pacific. During the cold ENSO period of 1988, the southeast trade winds extended into the western Pacific and equatorial upwelling was apparent from the measurements at 165°E (Fig. 5). From August to January equatorial SST was up to 1°C cooler than SST at 5°N or 5°S. Thermocline oscillations with approximately a monthly period were apparent in the surface relative to 300-db dynamic height at 5°N, 165°E, but not at the equator or 5°S. This signal appeared in boreal fall and disappeared in the spring, which is similar to the instability waves in the eastern Pacific. An associated SST perturbation was also apparent at 5°N. However, since lateral temperature gradients were weak, the instability wave signal in SST was less than 1°C. Dynamical investigations of these waves in the western Pacific are underway.

Ongoing studies with the TAO array data are investigating the heat budget of the equatorial region (McPhaden and Hayes 1990; Hayes et al. 1991); the Rossby-gravity wave signals in the equatorial wave guide (Hayes et al. 1989a); and the comparison of GEOSAT sea level with surface dynamic height inferred from ATLAS temperature measurements (Delcroix et al. 1991). As the array has expanded and the additional data has become available on GTS, the TAO array measurements are available for assimilation into operational atmospheric models and the experimental operational ocean model (Leetmaa and Ji 1989). Effects of these assimilations need to be examined and comparison of model and observed fields need to continue. In addition, as new sensors and analysis techniques are used to derive wind and surface elevation fields from satellite measurements the *in situ* observations of the TAO array will provide ground truth validation of the remote measurement techniques.

4. TAO array plans

Improvements in the ability to model the tropical Pacific Ocean (Leetmaa and Ji 1989) and the development of statistical and dynamical models to predict some aspects of the evolution of ENSO (Barnett et al. 1988) have led to a re-evaluation of the tropical Pacific Ocean observing system and recommendations for enhancements during the second phase of TOGA (US TOGA 1989; National Research Council 1990). A major focus of this observing array is to provide a surface wind field which is adequate to force existing tropical Pacific Ocean models and a description of the oceanic response which can be used to investigate the validity of these models. Data from the observing array should be available in real-time so that it can be assimilated into operational atmospheric and oceanic models. The real-time measurements and the model-based analyses allow diagnosis of the current state of the tropical Pacific and provide the basis for the prediction of the future evolution.

Ocean GCM simulations of the 1982-83 ENSO warm event and of the annual cycle have amply demonstrated the need for improved surface wind fields. Harrison et al. (1989, 1990) compared GCM simulations of the tropical Pacific in 1982-83 forced with five different surface wind fields, each of which was supposedly representative of the true wind field. All simulations were qualitatively similar; i.e., a warm event began in late 1982 and persisted into mid-1983. However, quantitative comparisons showed differences which were often as large as the observed anomaly (e.g., rms SST deviations between the model simulations and the observations were 2°-3°C). No wind product yielded the best simulation for all fields.

Design criteria for a tropical Pacific wind array have been developed using GCM simulations and analyses of historical data. Harrison (1989) demonstrated that simulation of the equatorial Pacific oceanic response during 1982-83 only required knowledge of the wind field in the equatorial wave guide (±7° latitude in his calculations). However, in the zonal direction, basin-wide fields were important; e.g., modeling the eastern Pacific response required both local and remote wind fields. The spatial resolution required to characterize the equatorial Pacific wind field cannot easily be obtained from these model studies which used monthly averaged fields. However, analyses of the wind time series measured at island stations in the central equatorial Pacific suggest that correlation scales are about 10° longitude and 2° latitude (Harrison and Luther 1990). These scales may be somewhat longer in the eastern Pacific and shorter in the western Pacific, but they serve as a reasonable starting point for array design.

Figure 6 shows the planned TOGA-TAO array which is based on the model and data studies of the surface wind field. This array has a total of 65 elements and spans the tropical Pacific from 95°W to 130°E. At each longitude the nominal ATLAS locations are ±8°, ±5°, ±2°, and 0°. Embedded in this ATLAS array, other investigators plan long term measurements of equatorial velocity at five sites (denoted by the squares on Fig. 5). Furthermore, process studies, such as the Coupled Ocean Atmosphere Response Experiment

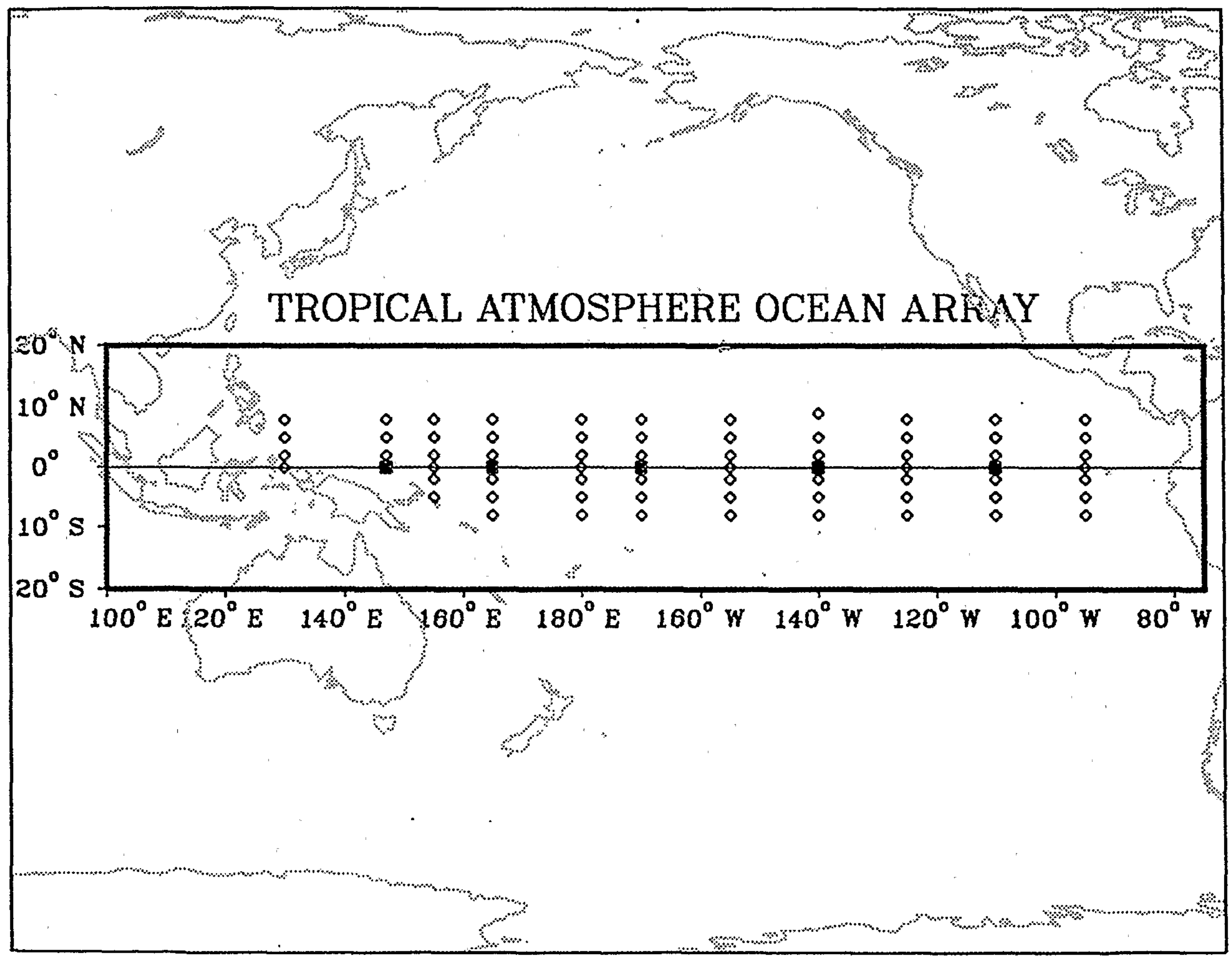

Fig. 6. The planned TAO array for the second half of TOGA. ATLAS moorings, denoted by the diamonds, will be deployed at the nominal locations of 8°N, 5°N, 2°N, 0°, 2°S, 5°S, and 8°S approximately every 15° of longitude from 95°W to 130°E (the southern portion of the array is blocked by islands in the western Pacific). Embedded in this array are equatorial current moorings at the five locations indicated by the squares.

(TOGA-COARE) in the western Pacific will provide enhanced regional coverage.

The TAO array in Fig. 6 will measure the basin-wide fields of surface wind and upper ocean thermal structure needed to describe and model the tropical Pacific Ocean. In addition to the basic parameters measured by the ATLAS moorings described above, the updated ATLAS will also measure relative humidity and near surface salinity. In order to satisfy a variety of users who are interested in both real-time and delayed mode data, the ATLAS will sample and average as follows: wind will be sampled at 2 Hz for 6 min out of each hour (3 min before until 3 min after the hour) and these data will be vector averaged. Scalar variables will be sampled every 10 min. The most recent hourly average value of all surface parameters (wind, relative humidity, air temperature, and SST) will be telemetered via ARGOS. In addition, the daily average of all data (surface and subsurface) from the previous day will be transmitted. In order to reduce power consumption, the ATLAS will only transmit during two 4-h windows each day. Hence, not all hourly data are available in real-time. However, these data are all recorded internally and can be used in subsequent research analyses.

Deployment of the enhanced TOGA-TAO array will require continuation and expansion of the international collaboration which initiated the basin scale array now in place. Our first efforts will be in the western Pacific where in 1991 we plan to deploy the 155°E line and complete the 147°E and 165°E lines as part of our multinational (U.S.A., France, and Japan) effort. Additional international collaborations are being pursued. Major expansion of the array will continue in 1992 and we expect to have the full array in place by early 1993. This research array will be maintained for a 2-year period. Based on evaluation of these measurements and their contributions to the operational ocean and atmosphere modeling programs, the research array will transition into an operational array needed to continuously monitor the tropical Pacific for ENSO prediction.

The TAO array is a major element of the ocean observing system in the 1990s. In addition to its principal purpose of low frequency monitoring, it offers many opportunities for analyses and collaborations. All real-time data are available on GTS, and the delayed mode research data are available through the NODC. Furthermore, additional sensors may be accommodated on the TAO array platforms on a not-to-interfere basis. Investigators interested in collaborating in TOGA-TAO should contact the TOGA-TAO Project Office, Ocean Climate Research Division, Pacific Marine Environmental Laboratory/NOAA, Seattle, WA, 98115.

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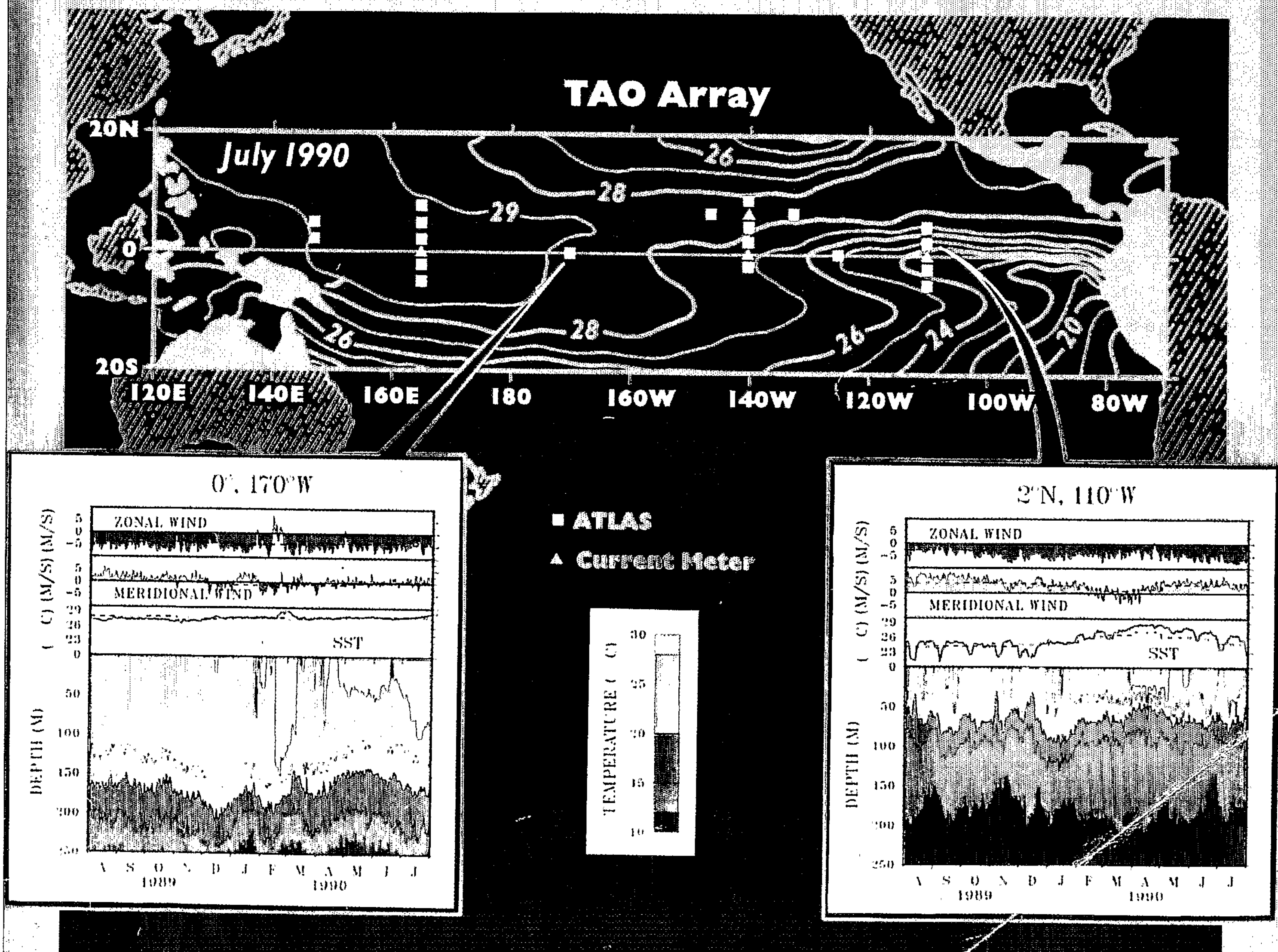

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