International Workshop
for review of
The Tropical Moored Buoy Network

10-12 September 2001
Seattle, Washington, USA

Workshop Report
June 2002

INTERNATIONAL WORKSHOP

for

REVIEW OF THE GLOBAL TROPICAL MOORED BUOY NETWORK

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Conducted under the auspices of
The GCOS/GOOS/WCRP Ocean Observations Panel for Climate
The CLIVAR Ocean Observations Panel
and
The JCOMM Tropical Moored Buoy Implementation Panel

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TAO/TRITON Teacher at Sea
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EXECUTIVE SUMMARY

At the Fifth meeting of the Ocean Observations Panel for Climate, it was agreed that it would be useful and timely to assess and review the contributions to the global observing system from the tropical moored buoy network. Consequently, in collaboration with the (former) Upper Ocean Panel of the Climate Variability and Predictability Programme and the Tropical Atmosphere-Ocean Array Implementation Panel, Terms of Reference were agreed for a study and review of the global tropical moored buoy network. The review was supported by a Scientific Organizing Committee and a consultant (Dr. P. Chapman) engaged by the U.S National Oceanic and Atmospheric Administration (NOAA). The input and preliminary conclusions of the study were discussed and debated at an international workshop, held at NOAA's Pacific Marine Environmental Laboratory during the period 10-12 September, 2001. The aim of the workshop was to review the societal and scientific rationale for a tropical moored buoy network, to establish a set of metrics for ongoing evaluation, and to recommend future developments in the context of continuing global ocean observations for climate studies.

Societal rationale and user perspective

Monitoring and prediction of El Niño remains the dominant rationale for the network's existence. However, the network is multi-faceted and serves many different purposes, at different levels. These include:

Fundamental, critical role[1]

- Real-time monitoring of seasonal-to-interannual variability, particularly in the tropical Pacific;
- Data for El Niño prediction models; and
- Understanding of variability and key processes for climate interactions, particularly in relation to intraseasonal and ENSO timescales.

Very important

- Winds for numerical weather prediction models;
- Air-sea flux determinations and testing of NWP models;
- Input to ocean prediction systems and associated services; and
- Understanding of ocean processes and variability.

Important

- Contributions to global SST estimates;
- Spatial and temporal context for short-term, regional-scale process studies;
- Provision of platforms for opportunistic research and applied studies; and
- Capacity building for the global ocean observing system and contributions to national infrastructure.

In total, these attributes provide a powerful rationale for maintaining and sustaining the tropical Pacific network and for developing similar sustained systems in the Indian and Atlantic Oceans. It is recognized that the existence of the network cannot by itself guarantee successful predictions of El Niño or other climate phenomena since such predictions require well-tuned, accurate models of the evolving ocean-atmosphere system. Additionally, there are inherent limits to predictability because of the natural uncertainties of the climate system. Nonetheless, the existence of a reliable moored buoy network has proven invaluable in monitoring and providing predictions for climate excursions and minimizing associated risks.

[1] In this summary, "fundamental and critical" are used to imply a role that is singular, of high priority, and cannot be replicated by any other observing system component. "Very important" is used to denote uses that have been accorded high priority but for which the role played by the tropical moored buoy network is not unique. "Important" is used to denote uses that are significant but for which the buoy network plays more of a supportive, rather than a leading role (see OOSDP (1995) for further discussion of this topic).

The user perspective provides general guidance on the design and implementation of the network. The most important aspects are:

- The tropical Pacific has the highest priority, with roughly equal importance attached to the surface and subsurface data;
- The Atlantic and Indian Oceans have strong scientific rationales but demonstrations of sustained, practical utility are pending;
- Timely, efficient delivery of data is essential;
- Integrated, multivariate data streams have high impact;
- The mooring arrays provide high quality data and datasets; and
- The network should be integrated with, and complementary to, other networks of the observing system.

Scientific impact and objectives

The scientific community continues to represent a key user group of high societal relevance. Research has provided and will continue to provide the best guide for the design and evolution of the network. This guidance is not precise and only indirectly factors in "user pull," but in its totality provides the first level of direction for optimal sampling and deployment of the network. The factors that must be considered include:

- Short time-scale, large space-scale ocean dynamical adjustments by equatorial Kelvin and Rossby waves, intraseasonal events and air-sea interaction in the vicinity of the equator favor a sampling approach that returns high temporal resolution data over broad regions of the equatorial zone;
- Characteristic wind forcing and equatorial dynamics lead to long zonal scales (order 1500 km) and narrow meridional scales (order 250 km), the first order constraint on spatial sampling;
- The vertical structure is characterized by strong stratification, dynamical adjustment and strong current shear;
- Off-equatorial time and space scales are less influenced by equatorial dynamics and time scales are generally much slower;
- The seasonal-to-interannual signals are large in the tropical Pacific, predominantly because of the El Niño phenomenon, and must be measured routinely. Interannual anomalies in the Atlantic and Indian Oceans are less pronounced; and
- Numerical weather prediction models tend to have systematic errors in the tropics and fixed mooring marine boundary layer measurements contribute to improved wind analyses and model boundary layer parameterizations; co-located multi-variate time-series measurements have been an important contributor to these improvements.

In addition, recent research has emphasized the importance of tropical moored arrays in providing improved understanding of the (intra-) seasonal-to-interannual and -decadal variability in the tropical oceans, and contributing to the monitoring of long-term change. Other areas where major advances in knowledge have been made on the basis of a fixed mooring approach include oceanic heat transport, wind-burst forcing, instability waves, and the variability of the hydrological cycle.

That the moored buoy arrays allow the collection of co-located measurements has been one of the most important aspects in these advances. Wide selections of data are available from moored arrays; they are consistent and obtained at considerably higher frequency than via other methods. It is anticipated that, in future, additional measurements will be obtainable from the moored arrays as new sensors with smaller power requirements become available.

Another major advance has been in the monitoring of surface fluxes. The moorings have proved excellent sites for this work, and are being incorporated into the global surface flux reference network. The high-frequency, accurate data obtained from the moorings have led directly to improvements in wind fields, boundary layer physics, and surface forcing functions. In addition, the mooring data have been used as the basis for several process studies, such as the Eastern Pacific Intensive Climate (EPIC) study, or the Tropical Ocean-Global Atmosphere Coupled Ocean Atmosphere Response Experiment (TOGA-COARE) in the far western Pacific warm pool. In both cases, the "core" moorings were enhanced both in number and in terms of the measurements carried out, but the existence of the basic array was a major factor in the implementation of each.

An additional reason for the tropical moored arrays, although not unique to them, is the information they provide on the hydrological cycle and on salinity variability. Such data are required by modelers, and will continue to be important even when the Argo array of profiling floats is deployed and if funding is secured for a satellite to monitor sea surface salinity. The moorings also provide sites for additional measurements such as carbon dioxide in the upper ocean. The servicing cruises provide researchers with further opportunities for sampling both within the array region and en route, and several other programs take advantage of these opportunities.

The Atlantic and Indian Oceans provide additional unique scientific challenges. There are known variations in climate and rainfall that appear to be related to changes in the tropical Atlantic, but we do not yet have the time-series that are necessary for complete understanding. In the Indian Ocean, even the basic data on seasonal-to-interannual variability are lacking, and a case can clearly be made for extending the mooring array into this region. However, vandalism to the moorings is a major problem that may demand changes in tactics in these oceans.

Spatial and temporal sampling strategy

The Workshop recognized the need for guidance on the evolution of the tropical moored array, but felt that, at present, no simple way exists to provide specific, detailed information. The initial mooring spacing in the Pacific was predicated on the time and space scales of the wind field and on the scales of equatorial dynamics. The U.S. CLIVAR program has specified closer spacing for tropical Pacific sampling (taken over all measurements). The Workshop discussed the need for closer zonal sampling around the equator to improve knowledge of the local divergence, but found no scientific justification for changing the present horizontal (zonal or meridional) sampling spacing of the TAO/TRITON array. The relative lack of data from the Atlantic and the complete absence of data from the Indian Ocean at present preclude any conclusions as to the requirements in these oceans, and continuing studies are needed to provide more specific guidance. Funding for such studies was perceived to be a potential problem area.

It was agreed that the region within about 5° of the equator is the most important domain within the tropics, with the equator itself clearly having the most importance. The impact of the tropical moored buoy approach is less further from the equator, except perhaps in the Indian Ocean where there is a major seasonal current reversal south of India (5°-8°N) and the role of the South Equatorial Current (near 10°S) in climate variability remains uncertain. There was a clear desire of participants to extend the Pacific and Atlantic moorings into the low latitude western boundary currents, as well as along the eastern boundaries, but vandalism may be the controlling factor in these regions. More frequent servicing cruises may help, but these have considerable cost implications.

The Workshop agreed that the high temporal resolution provided by tropical moored buoy networks, which has increased in the Pacific by one or two orders of magnitude for most measurements since the start of the program, is a unique and important feature. Such high-resolution sampling, much higher than from any other approach presently available, ensures that temporal aliasing is not a factor.

There was no strong argument for changing either the spatial or temporal sampling rates because of the availability of data from other networks. Once Argo data become available for an extended period, however, it will be important to assess the relative impact of the two monitoring systems, as well as that of other data platforms such as drifters and satellites.

It was accepted that there are limits to the number of vertical levels that can be instrumented on a mooring. However, it is recommended that attempts be made to increase the vertical sampling for particular parameters on certain moorings. While there is potential for sampling at deeper depths than at present, the general consensus was to improve sampling within the present sampling depth range. It is suggested that any initial expansion in the Pacific be made at equatorial heat flux measurement sites, and providing that fishing community vandalism does not render more heavily-instrumented moorings impracticable, at a limited number of off-equator sites along the EPIC line at 95°W in the eastern equatorial Pacific. It is also recommended that these sites could be used, in the same way as the BATS and HOTS sites off Bermuda and Hawaii respectively, for testing new equipment and experimenting with new data transmission methodology. Additionally, such a series of well-instrumented sites would allow researchers to study the interaction between the near-surface structure and the surface fluxes.

Fields sampled

The Workshop discussed the individual measurements taken on the moorings. It is apparent that there is an increased priority for air-sea flux measurements, and a strong interest in improving our knowledge of the hydrological cycle, i.e., a need for more and better salinity measurements. The importance of many measurements for validating models was noted.

Despite the availability of SST measurements from satellites (AVHRR, AATSR, microwave and geostationary), and evidence that the mooring data have very little effect on basin-wide estimates, there was little enthusiasm for ceasing to sample this parameter from tropical moorings. It was felt that sampling SST as part of a suite of co-located data far outweighed the relatively small cost savings that might result. At present, there is considerable discussion within the oceanographic community regarding the relative merits and importance of skin and bulk surface temperatures. The moorings sample bulk SST at about 1-meter depth. Given the ongoing discussion, the Review concluded the practice should be continued.

Surface salinity is now measured routinely from TAO/TRITON and PIRATA moorings. The Pacific data have proven valuable for studying salinity variability and for understanding the responsible mechanisms. Assuming that the SMOS and Aquarius missions to measure salinity by satellite proceed, then more in situ data from moorings and other platforms will be required for calibration purposes.

There was a clear agreement that the surface marine measurements from the moorings have improved the output of NWP models, and that the data quality is higher than that of other observing system elements. A new program is being developed within the research community to establish a network of heavily-instrumented reference sites; the tropical moorings provide extremely useful platforms for such measurements and their use for this purpose is encouraged.

Although wind measurements provided a major reason for establishing the TAO array during the 1980s, these data are no longer the dominant rationale for the mooring array. While there have been no data denial experiments using the wind data from the tropical moorings, it is anticipated that in the presence of regular satellite data tropical moored buoy data will have reduced importance for NWP products. While there is likely some measure of redundancy in wind measurements at present, the continuity of scatterometer data beyond 2005 is not assured, and the mooring measurements remain important for calibration and validation of the satellite data.

Subsurface temperature and salinity data are considered particularly important because they provide temporal sampling of the subsurface water mass structure that is presently not obtainable in any other way. It is recommended that samples be taken at 10-m depth within the mixed layer, particularly in the Atlantic. In the Pacific, such increased vertical sampling should be initiated at the heat flux sites on the equator. It is recommended that salinity sensors be added, at least to the sites having enhanced vertical temperature sampling. Later extensions should include off-equatorial moorings as well.

There was no clear view on the merits of high- and low-frequency basin-wide sampling for salinity. However, once Argo data become available, a study should be made to assess this requirement and the complementarity of mooring, Argo and ship-of-opportunity salinity data. If only low-density, low frequency salinity sampling is needed, this could perhaps be achieved through Argo, which will provide about 30 samples per day in the tropical Pacific.

There was considerable support for increased velocity measurements on tropical moorings, particularly near the surface where the shallowest sampling is presently at about 30 m depth. It is recommended that a limited number of moorings (most likely those used for heat flux measurements) be instrumented to monitor current velocities within the top 5-10 m of the water column. There was some support for the idea of adding current meters and/or ADCPs to other moorings, particularly along the equator (to monitor the local divergence and the Equatorial Undercurrent) or in low latitude western boundary currents. It was recognized, however, that this will have considerable financial implications and there are presently problems with transmitting ADCP data in real time. Near-surface velocity measurements are available from research vessels during servicing cruises, as well as from a combination of drifters, altimetry, and Ekman calculations. Thus, expanding tropical moored current measurements will require careful rationalization in the context of the overall observing system.

Overall sampling strategy

Regarding the overall sampling strategy, it was agreed that the science rationale has not changed markedly since the original deployments of elements of the TAO array. There is thus no scientific reason to change fundamentally the sampling strategy. At present, operational modeling systems exploit only the large-scale, low-frequency data, and these rather imperfectly. Research is the principal driver for the high-frequency data, and values highly the integrated, Eulerian properties of the data set.

While the Review accepted the continuing importance of the core measurements in the tropical Pacific and Atlantic, it is recommended that short-term (3-5 year) process studies be carried out prior to making permanent extensions to this core.

It was agreed that, at present, the tools do not exist to permit us to distinguish in detail the impact of individual components of the arrays (e.g., a particular mooring). Although models and data assimilation studies have been and will continue to be used, they are at present only guides at best. Thus, scientific judgement and consensus will be the main strategy that guides array development.

It was concluded that data communication rates could be a potential factor limiting the future effectiveness of the tropical moored arrays. The Iridium system of satellites, with its two-way data transmission capability, may provide an alternative means of data collection at higher bandwidth and a cheaper rate per bit. Experimentation with Iridium transceivers is encouraged, although it is recognized that redesigning the ATLAS hardware, software, and data processing protocols for Iridium will have major cost implications.

Metrics

While one aim of the review is to establish ways to monitor array performance, it is recognized that this evaluation cannot be separated completely from the assessment of complementary existing, or soon to be available, observation networks. To date, no such comprehensive assessment regime for the tropical moored buoy networks has been put in place, although some comparisons of individual elements have been done.

The metrics accepted at the meeting include those that cover both data collection and data utility. The former include such things as counts of observations by variable or instrument on a daily basis; the time taken for the data to reach operational centers; the rate at which quality control procedures are completed; the percentage of the data streams meeting quality control standards; and measures of the effectiveness of data transmission systems. Data utility includes statistics on the number of operational centers using the data, their scientific output in terms of published papers and reports, and comparisons of data with remotely-sensed (satellite) data and model output.

Additionally, there is a need to compare the data obtained from the moorings with those data obtained from other systems. A simple metric is to maintain statistics at cross-over points, for example where Ships-of-Opportunity pass close by moorings or satellite tracks pass over mooring sites. As satellite-derived sea surface salinity data become available, these should be compared with data from the moorings. This level of redundancy in the overall observing system is critical for assuring high quality and quickly identifying erroneous trends in instruments.

Finally, while the main use of the data is for estimating and predicting seasonal-to-interannual variability, we do not yet know in detail whether the array is optimal for predictive purposes. For the present prediction systems the Pacific array appears necessary and sufficient but for more advanced prediction systems the requirement for buoy data may be stronger or weaker. In the Atlantic the situation is less clear and questions are still being raised about whether the array design is optimal for meeting scientific objectives. The workshop recommended the development of a systematic, coordinated program of modeling and data assimilation to test and evaluate the impact of ocean data in ocean-only and coupled models, and thus develop metrics that better quantify the impact of tropical moored buoy data. Some of these are already in the pipeline as part of GODAE and CLIVAR, but others are needed. These cover aspects such as changes in data type and platform, sampling rate, and the impact of surface and subsurface fields in climate products.

Overall summary

While monitoring and prediction of El Niño remains the over-riding rationale, the present global tropical moored buoy network is multi-faceted and serves a number of different purposes. There was unanimous support for a tropical moored buoy network in the Pacific and elsewhere. The Review accepted that the tropical moored buoy networks are key elements of the present ocean observing system and provide important data for advancing science, for model development, and for climate prediction. Additionally, the Review agreed that for any conceivable global ocean observing system, such a network should provide the mandatory tropical “backbone” of the system. The present array in the Pacific has a record of dependability, provides high-quality data, and performs a major service not only to operational agencies requiring real-time data but also to scientists interested in the underlying processes driving variability in the tropical oceans and beyond.

Although the Pacific array is presently supported almost entirely by the U.S. and Japan, other countries, such as Chile, Ecuador, and Peru, have plans for expansion or have actually begun to expand the array to the east and south. These national initiatives are commended and should be encouraged, since they both contribute to the capacity of a global ocean observing system and provide additional data from a relatively undersampled region of the ocean that is strongly affected by ENSO.

In the tropical Atlantic, there has been a strong start with the PIRATA array, and the Review welcomed the initiative taken by Brazil, France and the U.S. in promoting and establishing the present array. The intent to transition the core portion of the array from research status to a sustained measurement system was welcomed, although it was recognized that at present, it is still difficult to identify its long-term value for scientific research and any societal applications.
The provision of the requisite ship time to allow more efficient and more frequent servicing of the PIRATA array was regarded as the most important single issue in improving data continuity. It is for the countries involved to determine whether this is best served by the provision of a dedicated ship, as is the case with the TAO/TRITON array, or whether alternative ways of overcoming the problems of data loss are possible. The same problem will arise if a long-term moored array is started in the Indian Ocean.

The interest shown by other countries in expanding the present tropical moored buoy network (e.g., Peru, Chile and Ecuador in the Pacific; Brazil, Morocco and South Africa in the equatorial Atlantic; India and South Africa in the Indian Ocean) suggests a perception at the national level of the importance and high priority attached to tropical moored buoy arrays. Sustaining this interest through capacity building is a crucial issue if we are to eventually establish a truly sustained, operational, global tropical moored network.

There is a strong rationale for continued support of the present tropical networks and for their extension into the Indian Ocean. The Review heard of firm proposals from India and Japan to deploy near-equatorial moorings in the tropical Indian Ocean, and of potential additional expansions. The Review commended such initiatives, since it believes the scientific and applied rationales for such expansion are strong. The Review encouraged the formation of a consortium of interested countries, both within and outside the region, that can together provide the necessary infrastructure and technical support to ensure the establishment of the Indian Ocean component of a global tropical moored buoy network.

1. **INTRODUCTION**

Interannual variability in the climate along the western coastline of South America, commonly referred to as El Niño, has been known at least since the time of the Spanish conquistadors (Wunsch, 1990), while fluctuations in the strength of the monsoons have been known for much longer (Philander 1989). Following the work of Bjerknes (1966, 1969) we now know considerably more about the coupled ocean-atmosphere relationship in the tropical Pacific (the El Niño-Southern Oscillation–ENSO). Similar phenomena are found in the tropical and extra-tropical Atlantic, the Indian Ocean, and even the Southern Ocean (White and Peterson, 1996), and it seems that atmospheric and sea surface changes are linked across much of the globe, with ENSO as a major driver. However, these linkages are neither obvious nor well understood. El Niños recur at intervals of between about three to seven years, and have widely different strengths, while there is also considerable, so far unexplained, interannual variability in the strength of the Indian Ocean monsoon.

During the 1970s, many researchers investigated aspects of ENSO variability, often through fieldwork and modeling programs such as the Equatorial Pacific Ocean Climate Studies (EPOCS; Hayes et al., 1986), the North Pacific Experiment (NORPAX; Wyrtki et al., 1981), or the Pacific Equatorial Ocean Dynamics (PEQUOD) experiment (Eriksen, 1987). However, a concerted effort to understand the whole process only commenced in 1985 with the birth of the Tropical Ocean - Global Atmosphere (TOGA) program, which lasted through 1994. TOGA was a major component of the World Climate Research Programme (WCRP), and had the following goals (WCRP, 1985):

1. To gain a description of the tropical oceans and the global atmosphere as a time-dependent system, in order to determine the extent to which this system is predictable on time scales of months to years, and to understand the mechanisms and processes underlying that predictability;

2. To study the feasibility of modeling the coupled ocean-atmosphere system for the purpose of predicting its variability on timescales of months to years; and

3. To provide the scientific background for designing an observing and data transmission system for operational prediction if this capability is demonstrated by the coupled ocean-atmosphere system.

A major component of the TOGA observational program was the initiation of a long-term, basin-scale, moored buoy array in the equatorial Pacific. The first TOGA moorings were deployed in 1984, and by the close of TOGA in 1994, an array was in place that spanned the Pacific between 8°N and 8°S at about 15-degree longitudinal spacing (the TAO array). The many uses for the data from these moorings have led to the establishment of a similar array (PIRATA) in the tropical Atlantic, and several groups and individuals have called for a tropical moored buoy array in the Indian Ocean as well. The growth of these moored arrays and the additional platforms that make up the present observing systems in the tropical oceans is discussed further in section 2 of this document.

It is not the intention to make this a review of the TOGA program. This has been done previously (e.g., NRC, 1990, 1994a), and the scientific results from TOGA have been published in numerous journals and conference reports (e.g., WCRP 1990, 1995a, NRC 1996). Similarly, there is a good overview of the theory linking changes in wind forcing in the equatorial Pacific to changes in sea surface temperature and currents in Philander (1989). This has been brought up-to-date in a series of papers in the Journal of Geophysics Research (volume 103, pp. 14,167-14,510, 1998) titled “The TOGA Decade: Reviewing the progress on El Niño Research and Prediction.”

Neither is this document a review of those at NOAA's Pacific Marine Environmental Laboratory and elsewhere who have labored hard over many years to bring the arrays in both the Pacific and Atlantic Oceans to their present state. The original aim of this report was to provide background information for a review of the present tropical moored array network in the Pacific and Atlantic Oceans and an associated Workshop, held in Seattle in September 2001. It has since been modified to reflect the discussion at that meeting. The review focussed specifically on the applicability and usefulness of the moored arrays that form the foundation of the observing systems in both oceans, and commented on possible changes to or expansion of the arrays to extra-tropical regions and to the Indian Ocean.

In this respect, the report will provide information for the ongoing development of the global observing system under the auspices of the Ocean Observations Panel for Climate (OOPC) of the Global Ocean Observing System (GOOS). The background to GOOS is given in a report by the Ocean Observing System Development Panel (OOSDP, 1995). The OOSDP Report requirements have been updated (IOC, 1999) as part of a continuing review and evaluation process, principally by the OOPC, and the latest information on strategies and potential applications is given in Koblinsky and Smith (2001). Thus this report on tropical moored buoy arrays is aimed at the same clientele as previous reports published by the OOPC on sea level (OOPC, 1998) and upper ocean thermal (GODAE, 2001) measurement systems.

Tropical moored arrays also will be a vital component of the WCRP-sponsored Climate Variability and Predictability (CLIVAR) program, part of which focuses on seasonal-to-interannual variability and prediction (WCRP, 1995b; NRC 1994b, 1998). Among other things, these documents specifically recommended that the TAO array in the tropical Pacific be expanded into the other two oceans. The CLIVAR Implementation Plan (WCRP, 1998) builds on this updated set of requirements. Finally, many research institutes and national weather centers are either using the data from the tropical moored arrays, or intend to use them, as data for their own predictions.

The terms of reference for the Seattle review were:

1. Review the societal and scientific rationale for a tropical moored buoy network in support of global climate and ocean forecasting, in particular predictions of ENSO, and the study of related oceanic and climate variability and predictability. The review should take account of experimental and operational applications, including long-term climate variability and change, and include moorings in all tropical ocean regions.
2. Document characteristics of the current data sets from the tropical moored buoy network including spatial (horizontal and vertical) and temporal sampling characteristics, logistical factors, data delivery, assembly and quality.
3. Document the accumulated data from the tropical moored buoy network including sampling, quality of delayed-mode data banks, length of records, integrity of data sets (including quality of metadata), and availability.
4. Assess the impact and relative priority of individual elements of the tropical moored buoy network, for both operational and research applications.
5. Examine the use of the tropical moored buoy network for calibration of satellite observations and as platforms of opportunity for other measurements such as carbon dioxide flux.
6. Establish a set of metrics for on-going evaluation of the network.
7. Provide a set of recommendations for the future evolution of the tropical moored buoy network in the context of the composite global climate observing system.

The tropical moored array network cannot, and should not, be reviewed in isolation. Section 2 of this report summarizes the contribution of moored arrays to the ENSO observation system in the Pacific as well as that of the Pilot Research Moored Array in the Tropical Atlantic (PIRATA), and includes a brief description of other measurement systems in these regions. Potential work in the Indian Ocean is also discussed. Section 3 provides details of the scientific knowledge gained from the arrays and applications of the data. The performance of the arrays is discussed in Section 4, and metrics for future evaluation are suggested in Section 5. Finally, a set of recommendations is given in Section 6. The over-riding conclusion was that the moored arrays are providing a valuable set of co-located data, many of which at present are unobtainable by other means. It was also agreed that the arrays should be maintained, and that their expansion should be supported.

Much of the information contained in this report was solicited from scientists who carry out research in the tropics and sub-tropics or use the data from the existing tropical moored arrays for operational purposes. Their views therefore express several different emphases–whether of university scientists or government employees, engaged in operational weather and climate forecasting, theoretical modeling studies, or analysis of in situ data. Such different perspectives give rise to different ideas as to the importance of individual components of the system. The meeting sponsors, organizing committee and chief editor of this document thank the contributors for their time and effort to make the review a success. The background documentation may be found at <http://www.bom.gov.au/OOPC/TMBN/>.

2. BACKGROUND

2.1 TOGA AND THE ENSO OBSERVING SYSTEM

The Tropical Atmosphere Ocean (TAO) array is merely one part of the ENSO observing system in the tropical Pacific. The main aim of this observing system is to provide the necessary data for improving our knowledge and prediction capabilities of the seasonal-to-annual changes that take place in this region. It is assumed that the basic mechanism, as given by Philander (1989) and in the J.G.R. special issue (1998), is correct and that it is unnecessary to repeat this description here. Good overviews of how the TOGA observing system was established are given in McPhaden et al. (1998, 2001), and much of the information in this section is adapted from these papers. The topic is also covered fully in NRC reports (NRC 1994a, 1998). The data requirements for the initial program in the Pacific (as in 1992), together with the present platform sampling capability, are given in Table 1. Note that this table differs from the present sampling requirements (Table 2) specified by JCOMM (GOOS, 1999). The growth of the observing system is shown in Figures 1 and 2. It should be noted that measurement systems and sampling rates have improved considerably from the original specifications. More details on this, together with information on present sampling rates, are given in section 2.2

As designed, the ENSO observing system contained four main parts:

- an island and coastal tide gauge network to provide sea level measurements;
- an array of surface drifters to provide mixed layer velocity and sea surface temperature (SST) measurements;
- the TOGA Tropical Atmosphere-Ocean (TAO) array of moorings to provide surface wind, SST, upper ocean temperature and current measurements; and
- a volunteer observing ship (VOS) meteorological program and an expendable bathythermograph (XBT) program for upper ocean temperature profiles.

Data from most of the platforms were transmitted ashore by satellite link in real time by the end of the TOGA program, using either Service Argos or geostationary satellites. Further dissemination was and remains via the GTS.

Table 1. TOGA data requirements (based on 1992 information) and sampling platforms presently available (adapted from McPhaden et al., 1998).

Parameter	**Horizontal (Vertical) Resolution**	**Time resolution (days)**	**Accuracy**	**Platform** [d]
Upper air winds	500 km (900 and 200 mbar)	1	$3\ m \cdot s^{-1}$	Islands, VOS
Tropical wind profile	2500 km (100 mbar)	1	$3\ m \cdot s^{-1}$	Islands, VOS
Surface pressure	1200 km	1	1 mbar	Islands, VOS, moorings, drifters
Total-column precipitable water	500 km	1	$0.5\ g \cdot cm^{-2}$	Islands, VOS, moorings, satellites
Area-averaged precipitation	2° lat x 10° long	5	1 cm	Islands, VOS, moorings, satellites
Global SST	2° lat x 2° long	30	0.5°K	VOS, satellites, drifters
Tropical SST	1° lat x 1° long	15	0.3°-0.5°K	VOS, moorings, drifters, satellites
Tropical surface wind [a]	2° lat x 10° long	30	$0.5\ m \cdot s^{-1}$	VOS, moorings, satellites
Tropical surface wind stress [a]	2° lat x 10° long	30	0.01 Pa	VOS, moorings, satellites, models
Surface net radiation	2° lat x 10° long	30	$10\ W \cdot m^{-2}$	VOS, moorings
Surface humidity	2° lat x 10° long	30	$0.5\ g \cdot kg^{-1}$	VOS, moorings
Surface air temperature	2° lat x 10° long	30	0.5°K	VOS, moorings, satellites
Tropical sea level	as permitted [b]	1	2 cm	Islands, altimetry
Tropical ocean subsurface temperature/salinity	as permitted [c]	as permitted [c]	as permitted [c]	VOS, moorings, Argo
Tropical ocean surface salinity	2° lat x 10° long	30	0.03	VOS, moorings, drifters
Tropical ocean surface circulation	2° lat x 10° long	30	$0.1\ m \cdot s^{-1}$	Drifters, moorings, altimetry
Subsurface equatorial currents	30° long (5 levels)	as recorded	$0.1\ m \cdot s^{-1}$	Moorings, Argo

(a) Accuracy requirements are given for 30-day averages, but daily values required to resolve 30- to 60-day oscillations
(b) Dependent on suitable island sites
(c) Dependent on suitable in situ measurement techniques
(d) Note that research cruises may also provide the same data as VOS vessels

Table 2. Tabulated Observational Data Requirements for GOOS/GCOS (from GOOS, 1999).

A summary of the sampling requirements for the global ocean, based largely on OOSDP (1995), but with revisions as appropriate. These are a statement of the required measurement network characteristics, not the characteristics of the derived field. The field estimates must factor in geophysical noise and unsampled signal. Some projections (largely unverified) have been included for GODAE.

Sampling Requirements for the Global Ocean							
Code	**Application**	**Variable**	**Hor. Res.**	**Vert. Res.**	**Time Res.**	**#samples**	**Accuracy**
A	NWP, climate, mesoscale ocean	Remote SST	10 km	-	6 hours	1	0.1-0.3°C
B	Bias correction, trends	*In situ* SST	500 km	-	1 week	25	0.2-0.5°C
C	Climate variability	Sea surface salinity	200 km	-	10 day	1	0.1
D	Climate prediction and variability	Surface wind	2°	-	1-2 day	1-4	0.5-1 m/s in components
E	Mesoscale, coastal	Surface wind	50 km	-	1 day	1	1-2 m/s
F	Climate	Heat flux	2° x 5°	-	month	50	Net: 10 W/m^2
G	Climate	Precip.	2° x 5°	-	daily	Several	5 cm/month
H	Climate change trends	Sea level	30-50 gauges + GPS with altimetry, or several 100 gauges + GPS	-	monthly means		1 cm, giving 0.1 mm/yr accuracy trends over 1-2 decades
I	Climate variability	Sea level anomalies	100-200 km	-	10-30 days	~ 10	2 cm
J	Mesoscale variability	Sea level anomalies	25-50 km	-	2 days	1	2-4 cm
K	Climate, short-range prediction	sea ice extent, concentration	~ 30 km	-	1 day	1	10-30 km 2-5%
L	Climate, short-range prediction	sea ice velocity	~ 200 km	-	Daily	1	~ cm/s
M	Climate	sea ice volume, thickness	500 km	-	monthly	1	~ 30 cm
N	Climate	surface pCO_2	25-100 km	-	daily	1	0.2-0.3 µatm
O	ENSO prediction	T(z)	1.5° x 15°	15 m over 500 m	5 days	4	0.2°C
P	Climate variability	T(z)	1.5° x 5°	~ 5 vertical modes	1 month	1	0.2°C
Q	Mesoscale ocean	T(z)	50 km	~ 5 modes	10 days	1	0.2°C
R	Climate	S(z)	large-scale	~ 30 m	monthly	1	0.01
S	Climate, short-range prediction	U(surface)	600 km	-	month	1	2 cm/s
T	Climate model valid.	U(z)	a few places	30 m	monthly means	30	2 cm/s

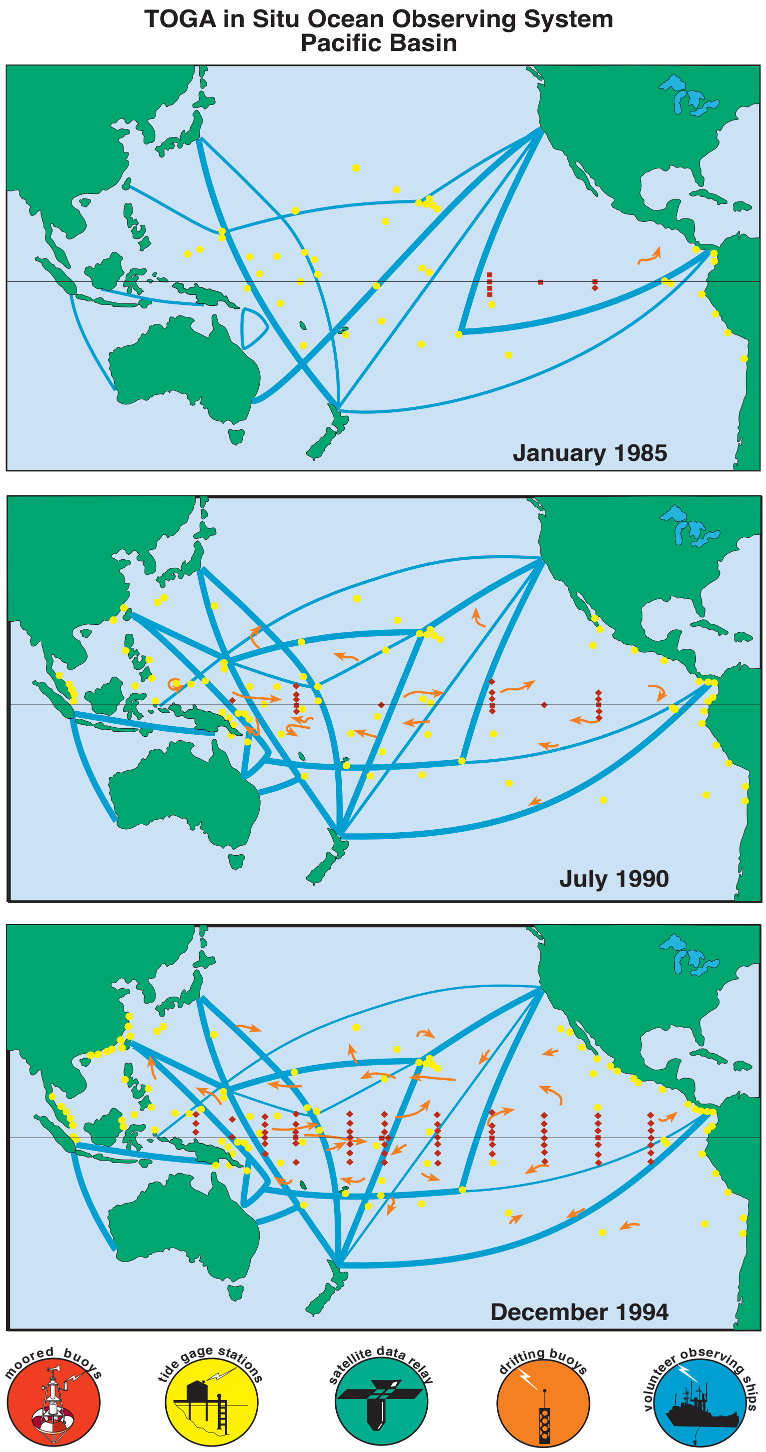

Figure 1. Growth of the in situ tropical Pacific Ocean observing system from the start of TOGA in January 1985 until its end in December 1994. The four parts of the system are: the VOS XBT program (solid lines), the tide gauge network (circles), the surface drifter program (schematic curved arrows), and the mooring network (wind and thermistor chains - diamonds; current meters - squares). Thick XBT tracks were occupied more than 11 times per year; thin tracks reported 6-10 transects (from McPhaden et al., 1998).

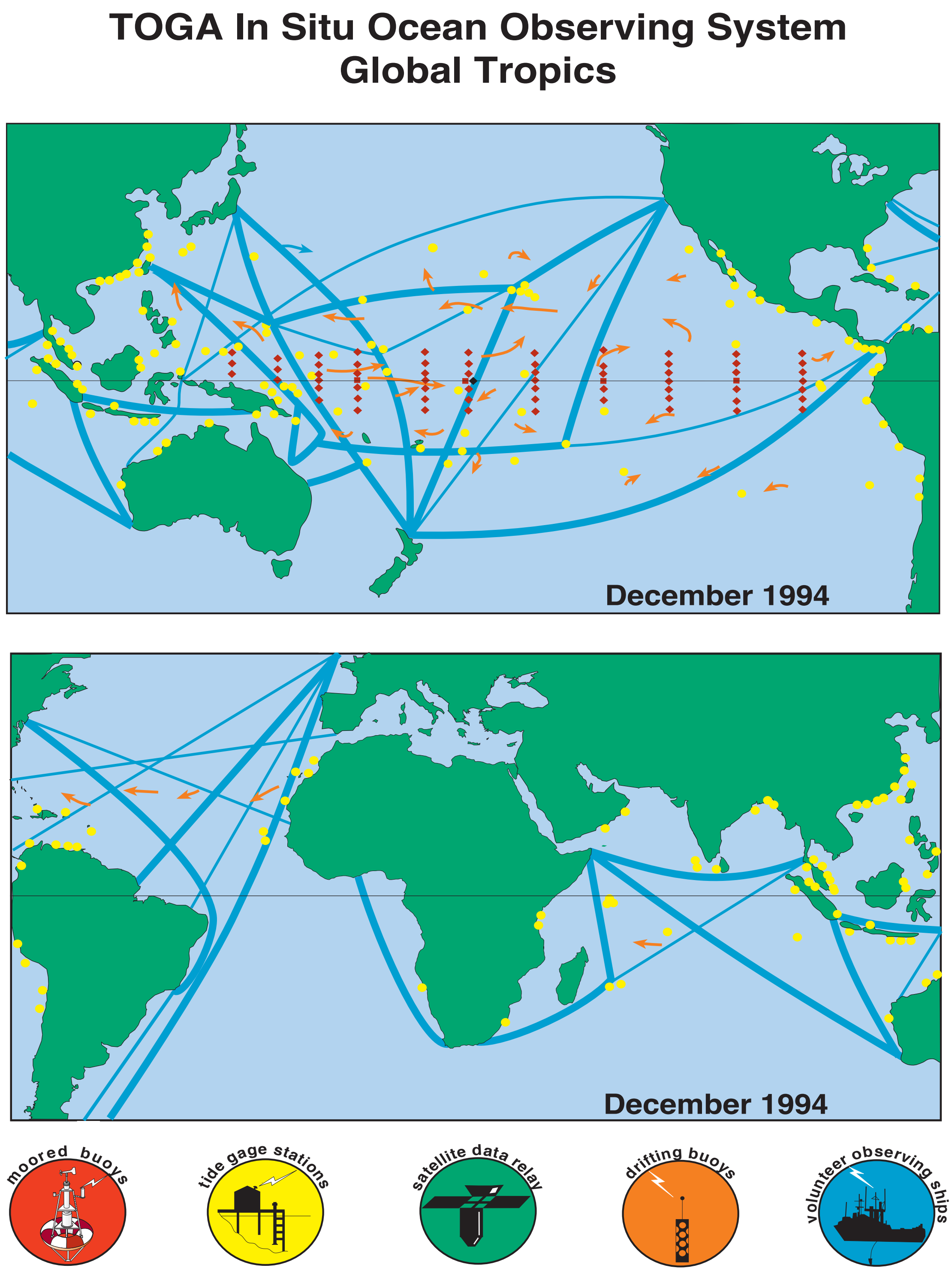

Figure 2. The in situ TOGA observing system in December 1994: (a) Pacific Ocean;□ (b) Atlantic and Indian Oceans. Symbols as for Figure 1 (from McPhaden et al., 1998).

In addition to the above, a sea surface salinity program, initiated in 1975, was incorporated into the system in 1985, while cruises of opportunity and repeated hydrographic occupations along meridional lines, some dating back more than 20 years, have provided further information on upper ocean water mass structure. Similarly, satellite data have been used throughout the program to monitor large-scale SST (by Advanced Very High Resolution Radiometers –AVHRR–on NOAA satellites), sea surface height (from Geosat, ERS-1/2, TOPEX/ POSEIDON), and surface wind speed (from SSM/I on DMSP, ERS-1/2, NSCAT/ADEOS, Quikscat).

The establishment of the different observing platforms required many compromises, and a list of the advantages and disadvantages of each is given in Table 3. For example, the establishment of sea level stations and the VOS lines depended on the availability of suitable island sites and commercial shipping routes. The current sea level plan is described in OOPC (1998). The aim of the VOS XBT deployments was to obtain one XBT profile per month in a box 1.5° in latitude by 7.5° longitude. On some lines, better along-track resolution was required to monitor seasonal variability within the tropical currents. On these high-resolution lines, probes are deployed on an hourly basis (approximately every 35-40 km) rather than the 150-200 km spacing on the normal lines. The ships also collect meteorological data as part of the World Weather Watch. Smith et al. (2001) describe the present strategy for ships of opportunity. This strategy assumes the presence of the TAO/TRITON and other tropical moored networks (specifically for ENSO prediction and estimating tropical variability) and of Argo (for providing wide-scale T/S information), among other things. In regions of rapid spatial and temporal variability, frequently-repeated XBT transects are recommended as a means of obtaining the water mass structure and variability of the upper ocean. As Argo becomes established, the existing broadcast (low-density) lines will be phased out. In specific regions, high-density XBT lines will be maintained in order to provide basin-wide constraints on the heat budget. Smith et al. (2001) argue that such a strategy complements the approach of tropical moorings.

The success of the drifters depended on the development of a reliable, low-cost instrument with a suitably long life and good water-following abilities. This was eventually achieved towards the end of TOGA (Niiler et al., 1995). Since then, the instruments have proved extremely useful during the global World Ocean Circulation Experiment (WOCE), providing data on both surface flow fields and SST, and their use will be continued as part of GOOS. Drifter life now averages 300-450 days, depending on location, and the instruments can be deployed from research vessels, VOS or airplanes. In addition to the standard SST sensor and transmission equipment, the instruments include a sensor that determines whether the drogue is still attached, and can be fitted with a barometer. Experiments on adding wind direction sensors are presently taking place (Niiler, pers. comm.). Sensor accuracy is about 0.1°C for SST, 1 mbar for pressure, and slip relative to the water column is reported as <1 cm s^{-1} in winds of 10 m s^{-1}. Location accuracy is about 300 m. The aim is to ensure enough drifters are present in each 2° latitude by 8° longitude box to define the mean 15-m circulation, the seasonal cycle, and ENSO-related anomalies.

2.2 THE TAO ARRAY

The use of moorings in large numbers could only be considered once a suitable technology was developed. The Autonomous Temperature Line Acquisition System (ATLAS) was developed by the Engineering Development Division of NOAA‘s Pacific Marine Environmental Laboratory under the guidance of the late Dr. Stan Hayes (Hayes et al., 1991), based on earlier current meter deployments in the equatorial Pacific (Halpern, 1987). This was a remarkable achievement, allowing the use of taut wire moorings in regions of strong equatorial currents and the telemetering of the data back to a shore laboratory. The first ATLAS moorings were developed and tested during 1983-1984, with the 110°W line of five moorings being in place in early 1985.

Table 3. Advantages and disadvantages of in situ elements of the TOGA observing system (from McPhaden et al., 1998).

Observing System Element	Primary variables Measured	Advantages	Disadvantages
TOGA-TAO	wind velocity sea surface temperature subsurface temperature (10 depths to 500m) ocean currents along equator (profiles to 250m)	real-time data delivery hourly/daily resolution Eulerian time series moderate horizontal/vertical resolution of seasonal and longer timescale variations mooring locations can be optimally fixed according to scientific design criteria permits estimates of dynamic height (baroclinic component of sea level) permits estimates of geostrophic currents and transports provides direct measurements or estimates of all critical TOGA variables platforms for additional oceanographic and meteorological instrumentation (e.g., salinity, solar irradiance, rain rate)	must be deployed from a research vessel subject to vandalism by fishermen relatively high cost per platform
Surface drifting buoys	sea surface temperature mixed layer velocity	real-time data delivery three-day resolution Lagrangian time series measures a wide spectrum of timescales/space scales can be deployed from VOS and airplanes relatively low cost per platform platforms for additional oceanographic and meteorological instrumentation (e.g., barometric pressure, salinity)	movements are unpredictable sampling potentially biased to convergence zones sparse sampling in equatorial cold tongue (meridional divergence zone)
VOS/XBT	temperature to depths of 450-700m	real-time data delivery deployed from VOS high vertical resolution high along-track resolution XBT probes inexpensive and of simple design permits estimate of dynamic height (baroclinic component of sea level) permits estimates of geostrophic currents and transports VOS also measures surface meteorology Salinity measurements possible from XCTDs and from VOS surface thermosalinographs	relatively coarse temporal resolution relatively coarse zonal resolution ship tracks determined by commercial shipping interests

Table 3. Advantages and disadvantages of in situ elements of the TOGA observing system (from McPhaden et al., 1998). (continued).

Observing System Element	**Primary variables Measured**	**Advantages**	**Disadvantages**
Island/coastal sea level stations	sea level	real-time data delivery stations relatively inexpensive to install and maintain high temporal resolution time series duplicate backup systems ensure high reliability some stations with very long records (dating back to the 1950s)	islands not necessarily optimally located (e.g., few islands in the eastern Pacific) data may be contaminated by local island or coastal effects only relative sea level differences between stations known

The rate of deployment of the system is shown in Fig. 3. Winds were added to the real-time data stream in June 1986, followed by humidity in November 1989. Rain and radiation measurements were added to the array along the equator in August 1991.

The standard moorings are equipped with a surface wind sensor, air temperature and humidity sensors, SST sensor and ten sub-surface thermistors, and two pressure sensors. The latter are positioned at 300 and 500 m depth, allowing corrections to be made to the depth of the temperature measurements if necessary. Nominal thermistor depth varies; in the eastern half of the Pacific they are positioned at 20, 40, 60, 80, 100, 120, 140, 180, 300 and 500 m depth, while in the western half they are at 25, 50, 75, 100, 125, 150, 200, 250, 300 and 500 m. These depths were chosen to correspond to the different stratification on either side of the basin. Daily averages and a few spot hourly values are transmitted to shore in real-time via Service Argos. An onboard data logger provides complete high-resolution data sets and allows the filling of any gaps in the real-time data records when the instruments are recovered. Support for the deployment and maintenance of the array has relied at one time or another on financial and logistical support from the U.S., France, Japan Taiwan, and Korea (McPhaden et al, 1998). France was the first to join the U.S. in 1985, followed by Japan in 1990 and Korea and Taiwan in 1992. At present, the array is supported principally by the U.S. and Japan. France contributes moored conductivity and temperature sensors for salinity measurements in the western Pacific, together with ship time on an occasional, contingency basis. In January 2000, Japan took over responsibility for all moorings west of 165°E, and the array was renamed the TAO/TRITON (Triangle Trans Ocean Buoy Network) array. French support comes from the Centre IRD (formally ORSTOM), while Japanese funding is provided by JAMSTEC.

US support for ship time, equipment, and technical staff is provided primarily by NOAA, where the necessary infrastructure in terms of manpower and data management has been built up over 25 years. Provision of ship time is the largest single commitment to the system, and is absolutely critical to the success of the program. Since 1997, the NASA/Tropical Rainfall Measuring Mission office has provided some funding, and 25 sites are now instrumented for rainfall and surface salinity measurements in the TAO portion of the TAO/TRITON array. Also since 1997, the Department of Energy's Atmospheric Radiation Measurement program has provided support for short wave radiation measurements along 165°E. A large amount of information on the history of the array, data returns, and current data, is available from the TAO/TRITON website at: http://www.pmel.noaa.gov/tao/.

The design of the TAO array was rationalized primarily in terms of the need for improved wind analyses (Hayes et al., 1991). Model simulations of the 1982-1983 El Niño event showed that meridional coverage along the equatorial wave guide (7°N-7°S) would suffice provided the measurements spanned the whole Pacific Ocean (Harrison, 1989), and suggested that correlation scales were about 10° longitude by 2° latitude (Harrison and Luther, 1990). The present array has 67 ATLAS and TRITON moorings between 8°N and 8°S, 95°W to 138°E (Fig. 2). Nominal locations are at ±8°, ±5°, ±2°, and on the equator at each longitude. At 147°E, 165°E, 170°W, 140°W and 110°W the equatorial moorings are fitted with point current meters for subsurface velocity measurements, while ADCP moorings are deployed nearby. Mooring lifetimes are twelve months, although servicing for possible repairs takes place every six months. Servicing the full suite of moorings demands dedicated ships, supplied by the U.S. and Japan.

Standard ATLAS moorings originally developed for the array have been slowly phased out and replaced by new NextGeneration ATLAS moorings (Milburn et al., 1996). The newer systems allow for real-time salinity, rainfall, shortwave and longwave radiation, ocean currents, and barometric pressure in addition to standard measurements. The sampling rates have also been increased considerably compared with those given in Table 1. On NextGeneration ATLAS, data are recorded internally every 10 minutes except for rainfall (1 minute), short-wave radiation

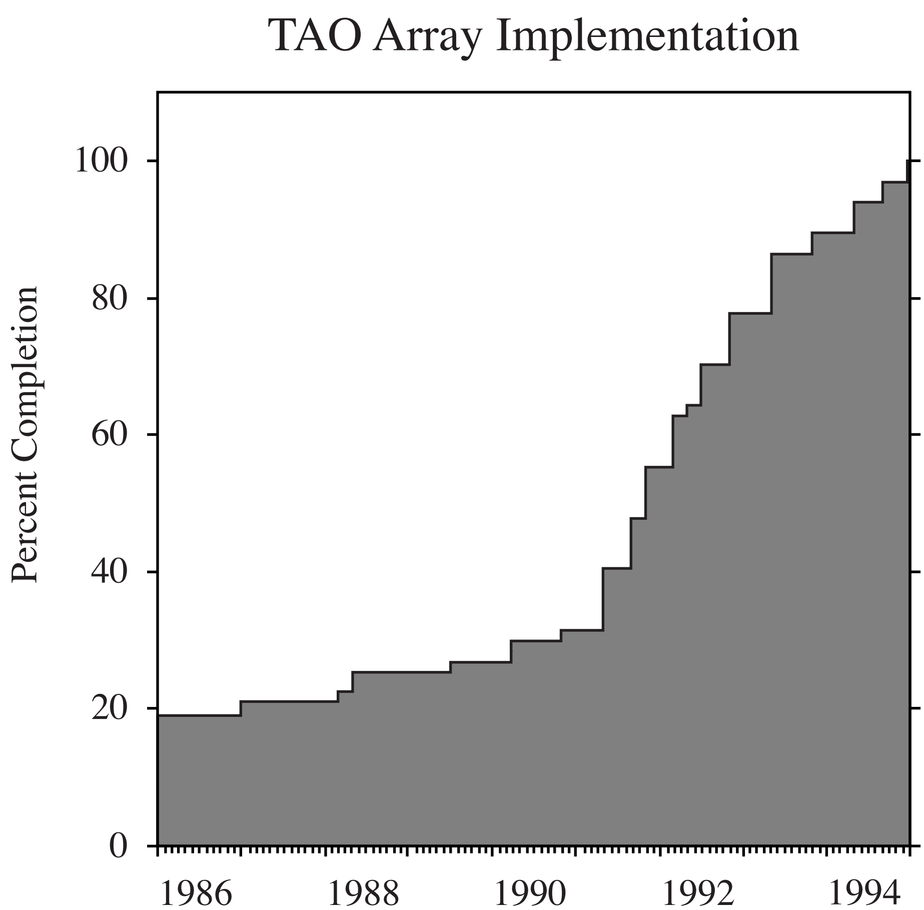

Figure 3. Rate of deployment of TOGA-TAO moorings (courtesy M. McPhaden).

(2 minutes) and barometric pressure (hourly). These new moorings have considerably improved instrument resolution and accuracy compared to the criteria in Table 1. According to Freitag et al. (1995, 2001), instrumental accuracy is about 0.03°C for SST, 0.2°C for air temperature, <0.1°C for subsurface temperature (Standard ATLAS) and 0.01°C for NextGeneration ATLAS, and 0.3 ms^{-1} (or 3%, whichever is the greater) for wind speed in the rage 1-20 ms^{-1}. The accuracy for relative humidity has improved from about 4% when measurements began in the late 1980s to about 3% since 1996 as a result of improved calibration facilities and instrumentation (Lake et al., 2002). Rainfall is measured with a siphon gauge (instrumental accuracy about 0.4 mm hr^{-1}), while short-wave radiation is measured with a precision spectral pyranometer (2% relative accuracy). Details of the current meter mooring design and velocity measurement accuracy are also given in Freitag et al. (1995). A full list of sensor accuracies and ATLAS sampling characteristics is available on the web at http://www.pmel.noaa.gov/tao/proj_over/sensors.shtml and http://www.pmel.noaa.gov/tao/proj_over/sampling.html.

As stated above, data dissemination in real time occurs via Service Argos satellites, after which the data are distributed via the GTS. Real-time data availability improved greatly during 1992 from about 10-30% to 80-90% following resolution of problems with the Argos-GTS link (McPhaden et al., 1998). In addition, delayed-mode data access has been encouraged through the development of anonymous file transfer protocols and access to data and products via the World Wide Web (Soreide et al., 1996).

Oversight of the development and operation of the array has been through the TAO Implementation Panel (TIP), established under the auspices of TOGA in 1992. Since the end of the TOGA program, sponsorship of the TIP shifted jointly to CLIVAR and the Global Ocean Observing System (GOOS) and the Global Climate Observing System (GCOS). The TIP dissolved itself at the conclusion of its ninth meeting, but has been reconstituted as the CLIVAR/GOOS/GCOS Tropical Moored Buoy Implementation Panel (also to be called TIP), with an expanded mandate that covers the global tropics and not just the Pacific. Emphasis also will change from scientific program planning to technical and logistical issues concerned with moored buoy arrays for climate research, as well as to capacity building.

2.3 THE TRITON ARRAY

Following testing of the TRITON buoys during the mid-to-late1990s, the first four moorings were deployed along 156°E in 1998. Since January 2000, JAMSTEC has been responsible for all moorings west of 165°E. All moorings west of 165°E have now been replaced by TRITON moorings. The complete TRITON array, which is scheduled to be completed in 2002, will comprise 18 moorings in the western Pacific and eastern Indian Oceans (Fig. 4). Funding for the array is assured for five years. The present moorings in the Pacific will be augmented with additional sites along 138°E and 130°E. However, despite much outreach to the fishing industries of countries in the region, and publicity through the Japanese Maritime Safety Agency, vandalism has been a major problem (see section 4 on Array Performance). Implementation has consequently been slower than planned.

Sampling at TRITON moorings is described in Table 4 (from Kuroda, 2002). All TRITON moorings take the standard set of measurements sampled on the TAO array, as described in section 2.2. Additionally, they all sample for salinity and include current measurements at 10 m depth. Standard recording of measurements is done every 10 minutes, while real-time data consist of hourly and daily means of these 10-minute records. Because of the ongoing vandalism, the moorings to be deployed at 130°E and on the equator at 138°E will not have meteorological instrumentation.

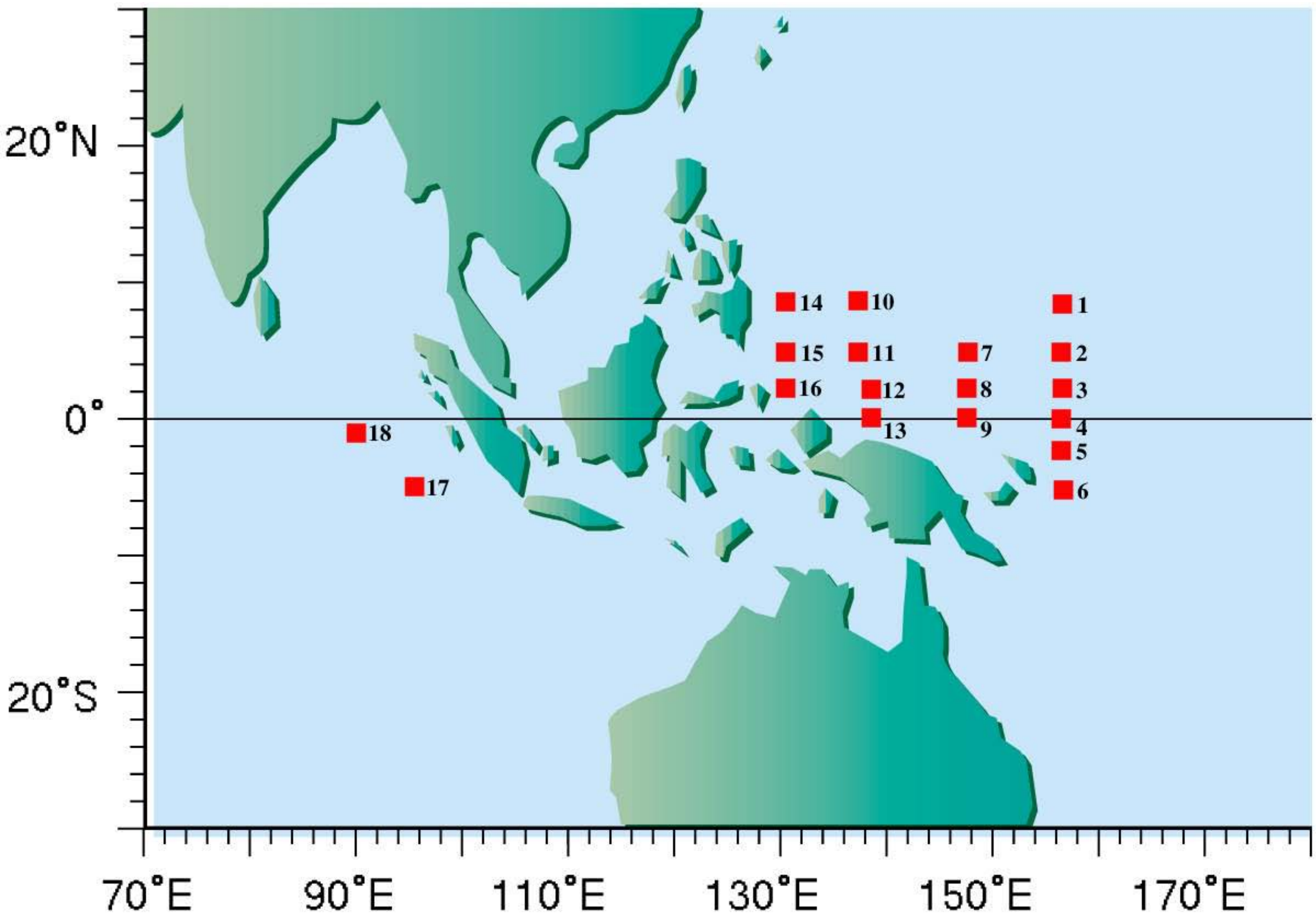

Figure 4. Distribution of the final TRITON mooring array (from JAMSTEC).

Table 4. TRITON sensor sampling (from Kuroda, 2002)

Sensor	Sample rate or response time	Average period in each sensor unit/ 1 sample	Sample period in TRITON data processor	Sample time	Data recorded in memory	Real time data (satellite transmission)
Wind vector Speed Vane Compass	1 per 5 sec 5 s integration 1 per 5 s 1 per 5 s	1 min- vector average	2 samples average /2 min	00:09-00:11 00:19-00:21...	every 10 min	hourly mean (ex. UTC 01:00 hourly data, 00:09-00:11 00:19-00:21... 00:59-01:01)
Shortwave radiation	1 per 2 sec	1 min-average	2 samples average /2 min	00:09-00:11 00:19-00:21...	every 10 min	hourly mean (same as above)
Relative humidity	1 per 10 sec	1 min-average	2 samples average /2 min	00:09-00:11 00:19-00:21...	every 10 min	hourly mean (same as above)
Air temperature	1 per 10 sec	1 min-average	2 samples average /2 min	00:09-00:11 00:19-00:21...	every 10 min	hourly mean (same as above)
Precipitation	1 per 5 sec	1 min-integration	10 sample integration/10 min	00:00-00:10 00:10-00:20...	every 10 min (ex. UTC 00:10 10-min data; 00:00-00:10)	hourly mean (ex. UTC 01:00 hourly data, 00:00-00:10 00:10-00:20... 00:50-01:00)
Barometric pressure	sensor response time less than 1 sec	no average	1 sample/10 min	0:10 00:20...	every 10 min	hourly mean (ex. UTC 01:00 hourly data, 0:10 00:20... 01:00)
CT/CTD	sensor response time 3.4-4.3 sec	7 sec-average	1 sample/10 min	0:10 00:20...	every 10 min	hourly mean (ex. UTC 01:00 hourly data, 0:10 00:20... 01:00)
Current vector	1 ping / 1 sec	2 min- vector average	1 sample /2 min	00:09-00:11 00:29-00:31...	every 20 min (since Oct. 2000 deployment; every 10 min before the deployment)	hourly mean (ex. UTC 01:00 hourly data, 00:09-00:11 00:29-00:31... 00:49-00:51)

Two TRITON moorings were scheduled for deployment in the tropical Indian Ocean during 2000 at 1.5°S, 90°E and 5°S, 95°E. The initial deployment was cancelled, mainly because of fears about the moorings dragging in the strong equatorial currents, but the sites were equipped with subsurface ADCP moorings. The first 16 moorings were deployed in October 2001 (Kuroda, 2002) and the full suite of moorings will be deployed in July 2002.

2.4 THE PIRATA ARRAY

Unlike the Pacific, the tropical Atlantic has two major modes of variability that are superimposed on the seasonal cycle; each describes about 20% of the annual variability (Servain et al., 1998). The first is an equatorial mode similar to the El Niño cycle (Hastenrath et al., 1987; Nobre and Shukla, 1996; Enfield and Mayer, 1997), while the second is an interhemispheric SST gradient mode (Nobre and Shukla, 1996; Enfield and Mayer, 1997). This second mode is related to latitudinal shifts in the position of the ITCZ and appears to affect the rainfall in both the African Sahel region and the Nordeste region in Brazil. While it is assumed that rainfall in the Nordeste of Brazil is linked also to ENSO and is predictable several seasons in advance, the relationship to date remains tenuous and the linkage to physical processes is not well understood. There are likely additional teleconnections to variability in the South Atlantic (Shannon et al.,1986), but as yet their forcing remains unknown.

More recent results, reported at the meeting on Tropical Atlantic Variability in Paris, 3-6 September 2001, suggest there is substantial coupling (both dynamic and thermodynamic) between the atmosphere and ocean in the tropical Atlantic, with potentially important roles for subtropical ocean cells and the meridional overturning circulation in climate variability. There is also evidence for coupling between the Atlantic tropics and the Arctic and North Atlantic oscillations, although the nature of this coupling is under debate at present.

Planning for the installation of a moored array in the tropical Atlantic began in 1995, when an organizing committee was formed during the 4th TAO Implementation Panel Meeting, held in Fortaleza, Brazil. The PIRATA program was designed as a three-year pilot system that would demonstrate the feasibility of establishing a moored array in the tropical Atlantic, as well as demonstrating its usefulness for weather and climate prediction. The operational goal was to establish a 12-mooring array and keep it in place for three years (1997-2000). This period has since been extended. The scientific background and implementation plan are given in PIRATA (1996) and Servain et al. (1998). Support for the program comes from the U.S.A., France and Brazil. Information on the data availability, sensor status, and other matters is available via the World Wide Web at: http://www.brest.ird.fr/pirata/piratafr.html, with mirror sites in the U.S. and Brazil.

Prior to establishing PIRATA, the tropical Atlantic oceanic data base was based on the VOS program, a few coastal and island tide gauges and a small number of surface drifters. In addition, surface coverage of SST and winds was available from satellites. Hydrographic cruises were infrequent, although the tropical Atlantic did receive some attention during WOCE. Virtually no subsurface measurements were taken–even the VOS XBT data did not allow subsurface temperatures to be calculated south of the equator to better than 0.4°C except along the shipping lanes (Festa and Molinari, 1992).

The specific scientific and technical goals of the PIRATA program are:
1. To provide an improved description of the seasonal-to-interannual variability in the upper ocean and at the air-sea interface in the tropical Atlantic;
2. To improve our understanding of the relative contributions of the different components of the surface heat flux and ocean dynamics to the seasonal and interannual variability within the tropical Atlantic basin;

3. To provide a data set that can be used to develop and improve predictive models of the coupled Atlantic climate system;

4. To design, deploy and maintain a pilot array of moored oceanic buoys, similar to the ones used during the TOGA program (the TOGA-TAO array) in the tropical Pacific; and

5. To collect and transmit via satellite in real time a set of oceanic and atmospheric data to monitor and study the upper ocean and atmosphere of the tropical Atlantic.

The array will be maintained to 2005 in a pre-operational phase and other nations may join in the maintenance and possible expansion of PIRATA. The array, an international research effort under the auspices of CLIVAR, is also a component of GOOS and GCOS in the tropical Atlantic. Expansion plans are currently being made through a program called COSTA (Climate Observing System for the Tropical Atlantic; COSTA, 2001), which will extend the array to cover the tropical Atlantic roughly between 20°N and 15°S.

The PIRATA array was designed to cover the regions along the equator with strong wind forcing (in the west) and with maximum seasonal-to-interannual SST variability (in the east). Mooring spacing (10-15° zonally and 2-5° meridionally) was chosen to resolve Kelvin wave responses to abrupt wind changes in the western equatorial Atlantic (Hackert et al., 1998) and to monitor the coherent structures in the surface boundary layer (Servain et al., 1998). Additionally, the mooring at 0°, 23°W was planned with an ADCP for monitoring current and transport variability in the Equatorial Undercurrent. The first two moorings were deployed in late 1997, four more in early 1998, with the remainder being deployed in 1999 (Fig. 5). In addition, wind measurements were inaugurated at St. Peter and St. Paul Rocks (0.7°N, 29.2°W) and Atol de Rocas (3.9°S, 33.5°W), while sea level measurements from Atol de Rocas, Sao Tome (0.5°N, 6.5°E) and Ascension (7.9°S, 14.4°W) were continued. The addition of a meteorological buoy by Brazil at 0°, 44°W was also planned.

PIRATA measurements include the standard measurements made in the Pacific (winds, air temperature, relative humidity, SST, subsurface temperatures and pressures) plus conductivity, rainfall and short wave radiation. The vertical temperature array is the same as for eastern Pacific ATLAS moorings. In addition, conductivity is measured routinely at the surface (1 m) and 3 additional depths (20 m, 40 m, 120 m). Sampling schemes and sensors are identical to those of Pacific ATLAS moorings.

Servicing of the moorings is carried out by Brazil in the west and by France in the east. This is done only on a 12-month schedule, unlike the TAO array. The U.S. is responsible for building the moorings, instrument calibration, equipment servicing, data quality control, web-based display and dissemination, and data archiving. As of May 2001, eight moorings were operational. The site at 2°N, 10°W was essentially lost in spring 2000, and the buoy was not replaced. At 2°S, 10°W the buoy drifted in early 2000. Although the surface mooring was recovered, the mooring was not replaced. The buoy at 0°, 10°W began drifting in early 2001 and ceased transmitting in mid-January. The 10°S,10°W mooring ceased transmitting in April 2001. Due to these and other mooring losses related to vandalism, PIRATA is now maintained as a 10-mooring configuration, without the sites at 10°W, 2°N and 2°S.

2.5 THE INDIAN OCEAN

It has been realized for some time that the Indian Ocean also shows interannual variability that is correlated with fluctuations in the Pacific. Several modes of variability are known, which may be related to ENSO (CLIVAR, 2000). These were first recognized at large scales by Walker (1924) and smaller-scale relationships are also known (e.g., Yasunari, 1987; Rasmussen et al., 1990).

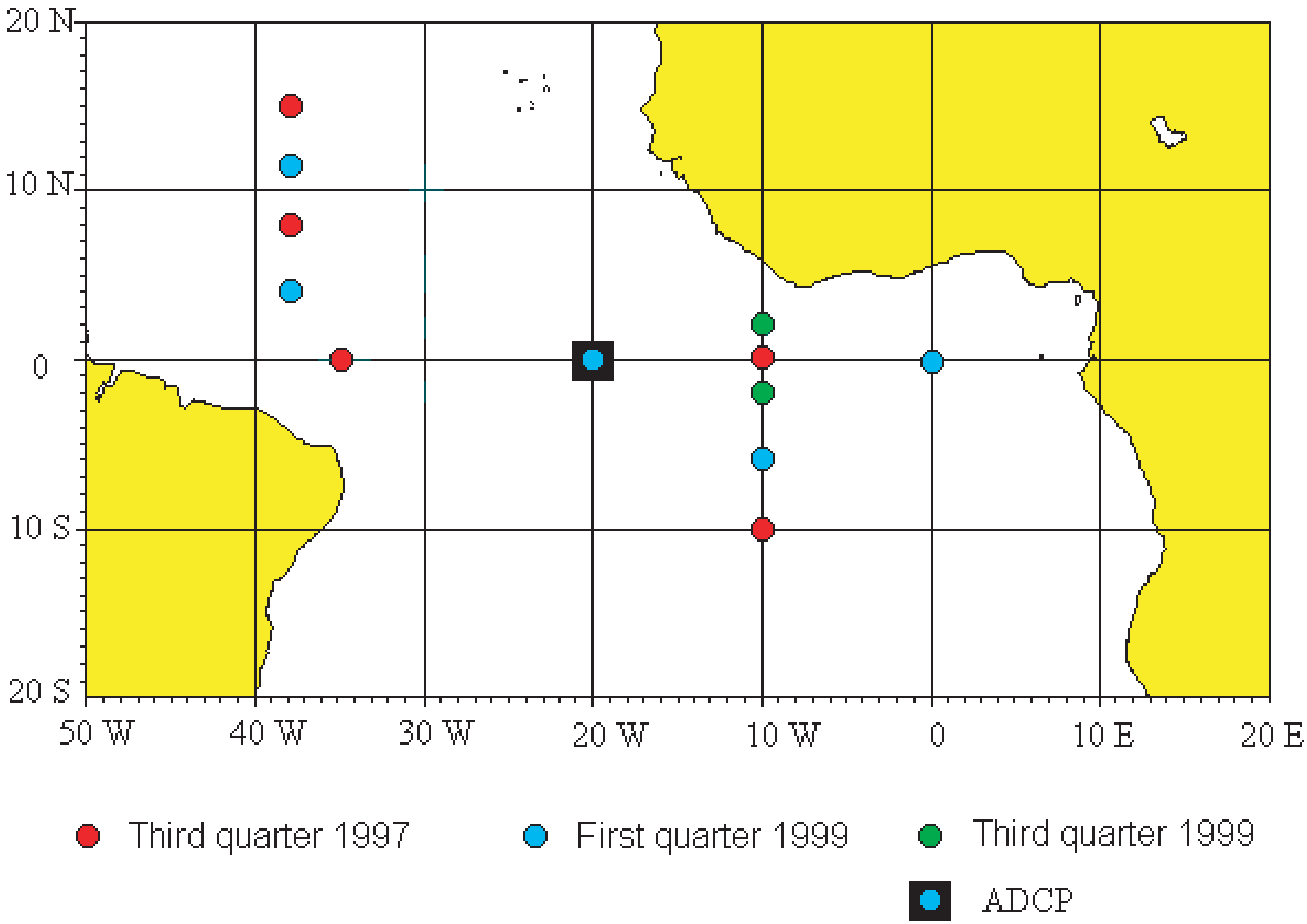

Figure 5. The PIRATA array, showing the development of the network during 1997-1999 (from PIRATA website)

More recently, an interannual Indian Ocean Dipole (IOD) in SST anomalies and rainfall has been identified by Saji et al. (1999) and related to internal oceanic processes that imply predictability. Further research is needed to determine if the IOD is an independent, unstable mode of variability unique to the Indian Ocean, or whether it results from ENSO activity further east. At intraseasonal timescales the boreal summer monsoon oscillates between active and break periods during its onset and evolution (Webster et al., 1998). Current research is seeking to quantify how the modes are coupled to annual and interannual variability, and to determine the degree to which they result from local coupled ocean–atmosphere processes. The role of the Indonesian Throughflow (ITF) in Indian Ocean variability also remains a topic of intense research. Model studies have implicated Rossby and Kelvin wave kinetics as affecting both SST and thermocline variability in the tropical Indian Ocean. The waves apparently propagate across the southern Indian Ocean near 5-15°S and into both the Bay of Bengal and the Arabian Sea (Schott, see OOPC/TMBN URL given on p.3). However, there has been little attempt until very recently to increase coverage of the tropical Indian Ocean. Given the importance to the region of the reversing monsoon winds and their associated variations in rainfall patterns, this is perhaps surprising.

At present, the Indian Government is supporting an array of 12 data buoys, due to increase to 20 in 2002-03 and possibly 40 later, around the coast of the country within India's EEZ. These moorings take data on wind, air temperature and pressure, wave heights, surface currents, SST and surface salinity every three hours. Additionally, a series of four subsurface current monitoring moorings, sampling six depths throughout the water column, is being deployed along the equator; the moorings at 0°, 93°E and 0°, 83°E are presently deployed, one at 0°,76°E was deployed early in 2002, with a fourth to be deployed later at 0°, 64°E. At least some of the data from the Indian surface moorings are being distributed via the GTS, but more could be done in this regard. As stated in section 2.3, JAMSTEC has deployed two TRITON moorings in the tropical Indian Ocean at 1.5°S, 90°E and 5°S, 95°E for a three-year pilot study.

The question of the need for coverage of the tropical Indian Ocean was noted by the U.S. National Research Council (NRC) review of observations in support of short-term climate predictions (NRC 1994a), which recommended the expansion of the tropical mooring arrays to cover all oceans. The WMO Commission for Marine Meteorology and the CLIVAR Asian-Australian Monsoon Panel have made similar recommendations (Meyers et al., 2001; CLIVAR, 2000). According to the Asian-Australian Panel:

> "Progress in identifying the role of ocean dynamics in the generation of SST anomalies has been rapid in recent years, particularly 1999, as demonstrated in presentations to the Panel [at their meeting in Hawaii, 6-7 December, 1999]. The progress can be summarized as a group of modes of variability including diurnal cycle, ISO, annual cycle, TBO, Indian Ocean dipole and decadal variation. The observing system must provide data on the essential, hydrodynamic fields associated with these modes, sustained long enough (>10 years) to understand the role of oceans in the Monsoons during the full range of climatic time scales."

The Panel suggested the deployment of four or five lines of TAO/TRITON moorings, equipped with current meters/ADCPs and subsurface temperature and salinity probes. Instrumentation to monitor surface heat and moisture fluxes should be mounted on at least some of them. The suggested lines are south of Java, west of Sumatera, in the central Indian Ocean (south of India), and in the western and far western Indian Ocean. These would be coupled with high-density XBT/XCTD lines north of 30°S, altimeter and Argo data, as well as to the expanded Indian coastal array. Because of the importance of freshwater run-off, good surface salinity data are an important requirement in the Indian Ocean.

A recent Workshop (Sustained Observations for Climate of the Indian Ocean–SOCIO), Perth, November, 2000) developed recommendations for the phased development of the sustained observing system in that region. Specifically, the Workshop goals were to:

Form a consortium of countries with interests in the Indian Ocean to
- Identify common interests in ocean observing systems
- Identify societal issues that require ocean data
- Review understanding of regional oceanic and climatic variability; and

Initiate multinational action-plans by
- Reviewing existing plans for sustained observations
- Surveying the need for data management, including historical data
- Initiating joint actions and seeking cooperation in proposals; and
- Considering outstanding issues such as carbon cycle measurements and hydrography.

The brief conclusions of the Workshop were:
- A sustained observing system is both desirable and doable;
- A Pilot SOCIO should be conducted during 2001-2005, with Argo floats and moorings playing key roles. The successful components should become part of a permanent system in the region;
- Process experiments will be required that provide synergy with GEWEX and other regional initiatives; and
- The suggested schedule exploits synergy with GODAE and GOOS.

The latest version of a proposed sustained observing system for the Indian Ocean is shown in Fig. 6. Subsequent to the workshop, several groups and individuals began to develop plans for a tropical mooring array in the Indian Ocean. These were reviewed at the August 2001 meeting of the CLIVAR Monsoon Panel. Tables 5 and 6 (courtesy of G. Meyers) provide a summary of existing or definitely committed moorings (Table 5) and proposed moorings for a sustainable equatorial array (Table 6). In addition, there will likely be moorings in Lombok, Ombai, Timor and Makassar Straits to monitor the Indonesian Throughflow. The intent is that, with the guidance of the CLIVAR Monsoon Panel and Ocean Observations Panel, together with OOPC, an implementation plan will be developed for a sustained observing system for the Indian Ocean incorporating tropical moorings as a major component.

One such pilot project (I-MAP, 2001) proposes an array in the western tropical Indian Ocean as a regional contribution to GOOS, as well as establishing a series of regional technical and application centers to convert the data into useful products. The array would cover the three western lines in Fig. 6 and would be instrumented with ATLAS moorings like those deployed in the TAO and PIRATA arrays. If funded, deployment will begin in 2004, and sample surface meteorology, temperature and salinity at 0, 20, 50, 100, 200 and 400 m, and currents at 50 m. This could perhaps be combined with proposals by U.S. investigators for moorings along the equator.

2.6 GENERAL REQUIREMENTS

Although the equatorial mooring arrays described in sections 2.2-2.5 were developed separately, there is now an internationally accepted set of general requirements for real-time observational data (Table 2). This was developed by JCOMM, based largely on the work of the OOSDP (OOSDP, 1995), but with appropriate revisions to cover the need for oversampling that will permit estimates of the errors. Koblinsky and Smith (2001) provide many examples of possible future programs, while details relating to specific needs for pilot, operational and sustained operations, based on user needs, are given in Nowlin et al. (2001). The essential requirement is

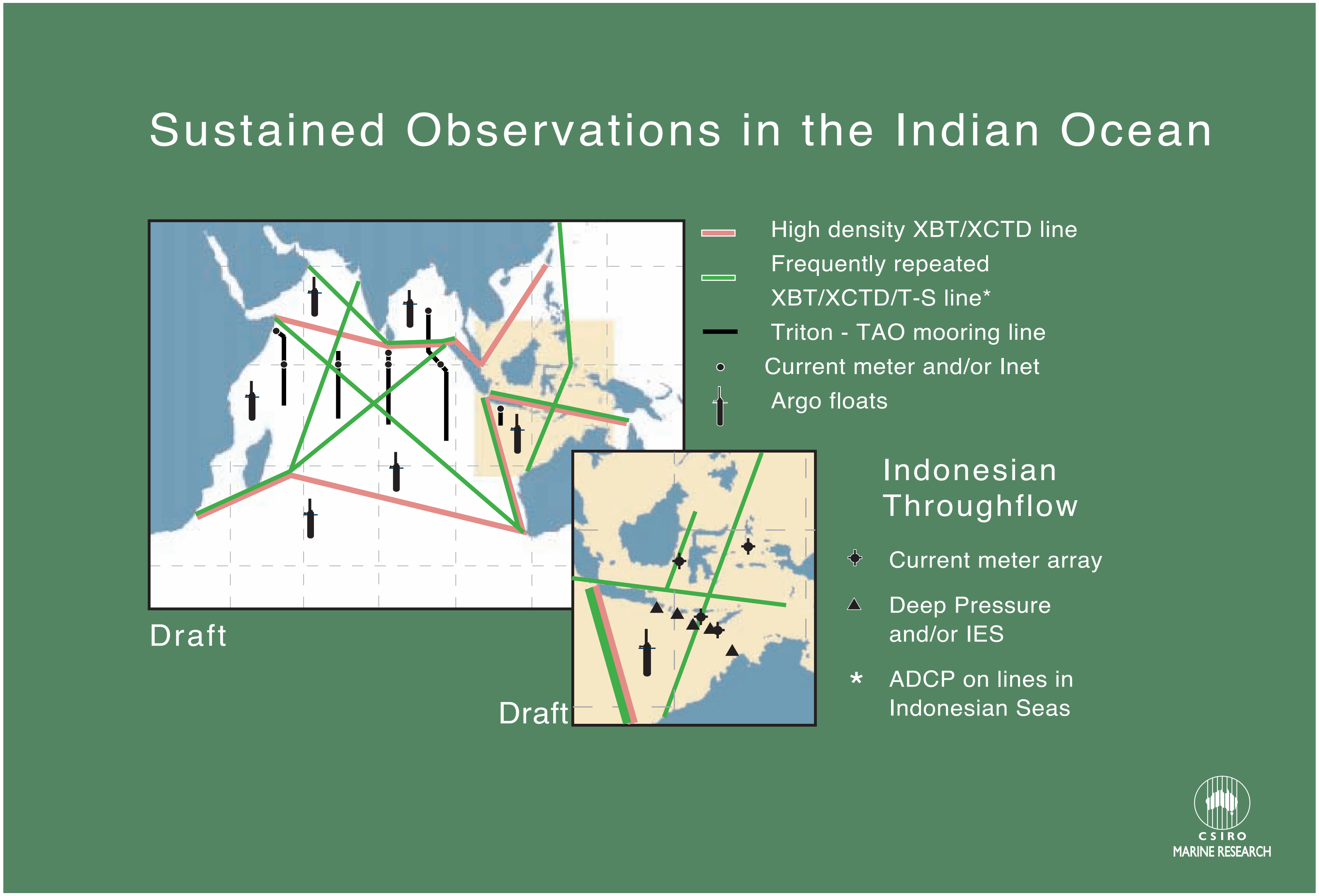

Figure 6. Proposed observing system for the Indian Ocean and the Indonesian throughflow (from G. Meyers).

Table 5. Existing or definitely committed tropical moorings in the Indian Ocean

Longitude	Latitude	Comment
53°E	0°	ADCP, not real time, India, no date
73°E	0°	ADCP, not real time, India, no date
90°E	0°	ADCP, not real time Japan, 2000
90°E	1.5°S	T/S TRITON real time, Japan, 2001-2004
93°E	0°	ADCP, not real time, India, no date
95°E	5°S	T/S TRITON, real time, Japan 2001-2004

Table 6. Proposed sustained equatorial array:

Longitude	Latitude	Comment
50°E	8°N	T/S, CM Is Somalia Current array feasible? Necessary?
50°E	0°	T/S, CM I-MAP and US CLIVAR Pre-Proposals India?
50°E	8°S	T/S I-MAP Pre-Proposal
65˚E	15˚N	OB-FL OceanObs 99
65°E	4°N	T/S I-MAP Pre-Proposal
65°E	0°	T/S, CM I-MAP and US CLIVAR Pre-Proposals
65°E	4°S	T/S I-MAP Pre-Proposal
65°E	8°S	T/S I-MAP Pre-Proposal
65°E	12°S	T/S I-MAP Pre-Proposal
60˚E	40˚S	OceanObs 99
80°E	6°N	T/S, CM Is Sri Lanka array feasible? Necessary?
80°E	0°	T/S,CM I-MAP and US CLIVAR Pre-Proposals India?
80°E	8°S	I-MAP Pre-Proposal
88°E	12°N	OB-FL OceanObs 99?
90°E	8°N	US CLIVAR pre-proposal.
90°E	5°N	CM US CLIVAR pre-proposal.
90°E	0°	T/S CM US CLIVAR pre-proposal, Japan? India?
90°E	1.5°S	Continue Japan deployment?
95°E	5°S	T/S CM US CLIVAR pre-proposal, Japan?
100˚E	25˚S	OB-FL OceanObs 99
110°E - 115˚E	8°S - 10˚S?	T/S CM Indonesia/Germany; US/AUS proposal. US CLIVAR pre-proposal

T/S Temperature and salinity by TAO or TRITON mooring.
CM Direct current measurements
OB-FL Ocean Observatory - air-sea flux site
All moorings include at least a basic flux package

for a sustained, coordinated and integrated global ocean observing system (GOOS) coupled to a system for data quality control, data dissemination, and archiving. The system should also undergo continuous review to ensure it fulfills the needs of both the research and operational communities and evolves as required to take advantage of improved, newer and cheaper technologies. This is not the place to discuss the GOOS, but it should be noted that all the above requirements for any global ocean observing system are equally important for the tropical moored buoy arrays.

Potential economic and social costs and benefits of a GOOS are considered by Flemming (2001). The main conclusion of this paper is that despite our present imperfect knowledge, when regional and larger scales are considered, and costs are projected far enough forward with a suitable discount rate, benefits appear to outweigh the costs. However, the necessity to work on these large spatial scales and long time scales demands cooperation between governments and other organizations to put the necessary infrastructure in place.

3. SCIENCE AND APPLICATIONS

Although a main aim of the tropical mooring arrays is the provision of data for forecasting (for example, for establishing the current state of the tropical oceans), the data are also widely used for scientific research, principally related to climate variability and predictability. This section contains a brief review of some of the different scientific and technical uses that are being made of the data from the various arrays. Most references refer to the Pacific, because the Atlantic data have not yet been utilized to the same extent, but it is anticipated that they will provide similar information on the tropical Atlantic. Contributors to this review have provided several updated descriptions of the most recent applications; these are included where possible. Since 1986, 400 refereed journal publications have made explicit use of TAO data, and another 700 unrefereed articles are also known, listed at http://www.pmel.noaa.gov/tao/proj_over/pubs.html#bib. Since 1995, between 30 and 50 refereed articles have appeared each year.

3.1 SCIENTIFIC AND TECHNICAL APPLICATIONS

A large number of specific topics which have benefited from the presence of the tropical Pacific mooring array and the other components of the ENSO observing system are discussed in the two papers by McPhaden and his co-workers (1998, 2001). A subset of these are listed below. As a result, only a few references are given in each section.

3.1.1. Improved knowledge of the long-term mean and the mean seasonal cycle

In order to explain and forecast the anomalies occurring as a result of ENSO phenomena, it is necessary to have a good knowledge of both the mean and mean seasonal cycle for several variables (e.g., SST, thermocline depth, surface wind stress) and their likely variability. Prior to the establishment of the TAO array, this was not possible for the Pacific because of the relatively poor quality of the data and the frequent gaps in sampling. Thanks to the array, we now have much better knowledge of features such as the warm pool in the western Pacific, equatorial currents, the cold tongue along the equator, or the cross-equator T/S structure, as well as how they are modulated on different timescales by forcing functions such as equatorial wave processes or changes in wind stress. The continued collection of data from the array will allow us to extend the records and perhaps elucidate how changes in global climate feed back into the tropical ocean-atmosphere system. In addition, they will continue to constrain models of the observed changes–at present few, if any, ocean general circulation models can model successfully both the mean state and its variability.

3.1.2. Improved knowledge of ENSO variability

The relationship between El Niño events and the Southern Oscillation can be seen very readily as a result of the data from the TAO/TRITON array. The Southern Ocean Index, for example, is clearly related to anomalies in SST or wind stress, with high values of the Index corresponding to La Niña episodes and low (negative) values to El Niños. Changes in the thermocline depth across the ocean are related to changes in both the heat content of the upper ocean and to the strength of the equatorial currents (e.g., Kessler and McPhaden, 1995), particularly the Equatorial Undercurrent, which feeds cold water to the eastern Pacific upwelling tongue (Bryden and Brady, 1985). This zonal variation in upper ocean heat content can also be followed as changes in sea level (e.g., Delcroix and Gautier, 1987).

It is generally accepted that equatorial eastwardly-propagating Kelvin waves and westwardly-propagating Rossby waves are of prime importance for the onset and ending of El Niño episodes. However, it is not yet clear what controls the transfer of energy between them to cause the switch from one state to another. The data from the array have led to several different theoretical ideas, including the delayed-action oscillator (Schopf and Suarez, 1988) and the advective-reflective oscillator (Picaut et al., 1997), which are being tested in models. This work could not have been carried out without data from the tropical Pacific array.

3.1.3. Kelvin waves, wind-burst forcing, and instability waves

Kelvin waves in the equatorial Pacific have energy corresponding to periods of 40-120 days, but they are concentrated near the 60-90 day period. The waves are known to be forced mainly by zonal wind variations associated with westerly wind bursts and the Madden-Julian oscillation (MJO) in the western Pacific, but the relationship is such that there is a shift to longer periods than shown by the MJO (Kessler et al., 1995). The westerly wind bursts lead to sudden changes in the current field in the upper 100-150 m of the water column, resulting in fast-moving easterly jets, which transport low salinity water into the warm pool and may lead to barrier layer formation (e.g., Sprintall and McPhaden, 1994). This variability in zonal current anomalies, and its effect on the warm pool, is a major component of the advective-reflective oscillator (Picaut et al., 1997). The extensive, high-quality, and well-resolved (in time and space) data from the tropical Pacific moorings have been instrumental in providing new insights regarding the relationship between wind forcing and propagating waves, as well as providing data on their importance during the 1997-98 El Niño (McPhaden, 1999).

Instability waves propagate westwards with long (1000-1500 km) zonal wavelengths and periods of 20-30 days. They are formed through shear instability at the edges of the zonal equatorial currents (Philander, 1978), and can act to slow down large-scale zonal flows. They also may affect the stability of the atmospheric boundary layer, cloudiness, latent heat distributions, and nutrient and other chemical distributions (e.g., Feely et al., 1994). Waves of similar character have been identified in the tropical Atlantic. While the spatial patterns of these waves may be resolved by either satellites or dense arrays of drifters, the TAO/TRITON and PIRATA data provide excellent temporal resolution of such phenomena.

3.1.4. ENSO-related surface salinity variations

Large-scale salinity variations across the equatorial region have been known for a long time, but only more recently has it been realized that local salinity variability is related to ENSO. During El Niño periods, the sea surface salinity (SSS) field west of 150°W and between 8°N and 8°S is fresher than normal, while poleward of these latitudes it is saltier than usual (Delcroix et al., 1996). The same is true east of 110°W within 10 degrees of the equator. During La Niña, the opposite occurs. The changes within the equatorial zone occur because of changes in rainfall and horizontal salt advection, particularly west of 165°W. Additionally, in regions of heavy rainfall, the formation of thin, low salinity barrier layers may reduce vertical turbulent mixing, thus leading to warmer SSTs and coupling the upper ocean heat balance to the hydrology (Lukas and Lindstrom, 1991). Such barrier layers are known in all three oceans, and were studied in depth during the TOGA-COARE program (Godfrey et al., 1998). However, the results of TOGA-COARE indicate the need for better SSS observations–to date, even a simple comparison between barrier layer thickness, SST changes and the displacement of the zonal salinity front at the eastern edge of the warm pool cannot be made because the requisite long time-series of salinity data does not exist. Similarly, the lack of salinity data leads to errors in dynamic height estimates and hence to errors in pressure fields inferred from altimetry (Ji et al., 2000). Additional salinity sensors on the TAO array could make a major difference in this area.

3.1.5. Variability and predictability of ocean currents

The failure of geostrophy near the equator means that direct current measurements are very important in this region. The tropical mooring array in the Pacific has provided the first long-term data on the variability of the equatorial current system and, in particular, on the changes in the Equatorial Undercurrent and South Equatorial Current during ENSO. Adding ADCPs and other current measuring instruments to TAO/TRITON moorings and to the additional moorings deployed during the TOGA-COARE program has led to new insights into the dominant transport signals in the western equatorial Pacific, their horizontal and vertical structures, and their variability on time scales from two days to several months (Kutsuwaba and Inaba, 1995; Ueki et al., 1998, 2000). However, there are still unexplained modes of variability in measured equatorial subsurface currents (e.g., below 250 m depth where 6-12-month variability has been found–Firing et al., 1998; Henin et al., 2000; Delcroix et al., 2001). Such variability likely affects the evolution of ENSO and interdecadal changes, but as yet we have no explanation for them.

Similar variability is found in the tropical Atlantic Ocean (COSTA, 2001). Additionally, in the Atlantic in particular, interaction between the tropical and subtropical circulation cells affects both the surface heat content and the mass transport. The northward energy transport across the equator must be converted from a geostrophically-controlled flow to one that is largely ageostrophic (COSTA, 2001). This means that there must be vertical circulation near the equator, as seen in the seasonal appearance of the equatorial cold tongue. Similarly, the strong northward-flowing western boundary current along the coast of Brazil counteracts the southward Sverdrup transport in the basin interior. Thus, current measurements are becoming more important than previously for modeling and prediction studies in both the Atlantic and Pacific Oceans.

3.1.6. Atmospheric variability induced by ENSO

While TOGA carried out considerable research on the upper atmosphere, this is not relevant to a discussion of tropical moored arrays. The data from the array have been used, however, to examine the relationship between horizontal pressure gradients and boundary layer winds. The results of this work led to more dynamically consistent interpretations of the effects of the ocean boundary layer (Nigam and Chao, 1996). Additionally, studies of the surface manifestation of the MJO in the western Pacific have led to new theories of the role of SST in convection at intraseasonal time scales, and hence to better simulation of the MJO in ocean-atmosphere coupled models. The data have also helped improve our knowledge of the feedback between evaporation and convection (Flatau et al., 1997).

3.1.7. Improved wind analyses and flux data

The original rationale for the tropical mooring array was largely concerned with the need to improve the timeliness and quality of surface wind data in the tropical Pacific, a region that was and continues to be a weakness of operational weather prediction models. Data from the TAO/TRITON array are being used presently in operational weather forecasts. Impact studies carried out at the European Centre for Medium-term Weather Forecasting (ECMWF) showed that analyses with and without TAO data could differ by more than 3 m s^{-1}, though typical differences were lower (Anderson, 1994). Also, unless new TAO data were added regularly, the model tended to drift away from the data. The data appear particularly useful in correcting low level winds, which suggests problems with the model description of the tropical boundary layer. Recent improvements in assimilation techniques have also allowed the TAO data to be assimilated directly into models. These have led to considerable improvements in wind analyses and gridded fields put out by groups such as Florida State University and NCEP. Now that Quikscat is providing regular global wind coverage, the role of the TAO/TRITON data for modeling and operational wind analysis and weather prediction may change, although they will still be needed for in situ ground truthing of satellite data (see section 3.4). In this regard, it should be noted that despite the success of the ERS satellites, the first operational scatterometer is not due to fly until late 2005, thus the wind data from the arrays will remain important for several years to come.

It should also be noted that there has been a considerable decline since the start of TOGA in the number of stations providing meteorological data. In situ meteorological measurements in TOGA derived from the World Weather Watch (WWW). The tropical WWW network deteriorated significantly during TOGA for various reasons (technical, political, and economic). This makes the data obtained from the mooring arrays more important for validating satellite-derived flux measurements, used for initiating forecast models, and moored buoys have been suggested as primary sites for obtaining such data on a routine basis (Taylor et al., 2001; Send et al., 2001). Several potential sites listed in these papers either coincide with or are close to tropical moorings, while many of the required measurements are already being collected at TAO/TRITON and PIRATA moorings. It would therefore be relatively inexpensive to make further use of the arrays in this manner. Thus, the existing tropical arrays could be more fully exploited for meteorological measurements and to satisfy surface flux requirements for research and forecasting purposes.

3.1.8 Assimilation of temperature and other data into ocean models

Ocean temperature data are being assimilated routinely into several climate prediction models (e.g., by ECMWF, NCEP, COLA, UKMO, and others). The tropical mooring arrays provide consistent, high quality subsurface temperature data for this purpose. Several studies have shown that the TAO subsurface temperature data improve analyses of the tropical Pacific temperature fields and positively impact the skill of ocean and climate prediction models (Anderson et al., 2001). The impact comes in at least two ways. First, the continual assimilation of equatorial subsurface temperature data corrects the mean state of the model thermocline, the position of which is important for equatorial adjustment and coupling of the upper ocean and atmosphere. This can be viewed as a correction of the state simulated using wind forcing and the model alone. Second, the data are able to initialize the low frequency modes associated with ENSO and thus provide a basis for improved predictability. The tropical mooring data are also routinely used to verify the model and improve its performance, and to verify predictions based on the initial condition developed from the data.

Developing empirical relationships between sea level and the baroclinic ocean thermal structure also allows sea surface height data, obtained from altimetry, to be assimilated into models. Such relationships also provide evidence that the altimetry data are being used to good effect.

The mooring data in the tropical Pacific have been used by the U.K. Meteorological Office to study the impact of assimilation of data into ocean model systems with significant systematic errors. Strong spurious circulations develop when standard techniques are used to assimilate the data. A technique for avoiding the spurious circulations has been developed (Bell et al., 2001). Further work in this area could help to diagnose deficiencies in the fluxes driving the oceans or in the parameterization schemes used by the models. Over-specification of data inputs can be used to enable systematic errors in the inputs and the models to be resolved.

3.2 CLIMATE PREDICTION

The main application of the data from the tropical moored arrays is for climate prediction, particularly as regards ENSO predictions and other variability on seasonal to interannual timescales. It seems fair to say that the installation of the TAO network was directly responsible for accurate observations of ENSO variability and for the beginnings of predictive skill in ENSO forecasting. Much of the predictable seasonal signal in the tropics is associated with oceanic conditions, because the large heat capacity of the upper ocean serves as a "memory" for the climate on seasonal to interannual time scales. Up to one season ahead, some aspects of climate variability can be predicted without using the subsurface ocean. However, beyond a few months, many studies have shown that adding the moored buoy data appears to increase substantially the subsurface accuracy of ocean analyses in the tropics (where model biases and other errors are known to be large), and hence the predictive capability of a model. As a result, the models can make more accurate forecasts for longer periods in the future. For example, the operational NCEP climate forecast system shows considerable skill at predicting ENSO episodes six to nine months in advance. Thus, any skill in the models is dependent on the assimilation of these data (Ji, see material at OOPC/TMBN URL given on p.3). However, very few users have carried out the comparative studies to allow them to estimate the improvements due solely to adding the mooring data to their model runs. This makes estimating the true value of the array difficult. Indeed, the relative shortness of the climate record, and of the tropical mooring data in particular, makes observing system sensitivity experiments with climate prediction models problematic. Any perceived positive or negative impact in model skill could just as easily be attributed to chance or systematic model errors as it could to a particular data input.

Many groups now run models of ENSO prediction, and the accuracy of their results depends strongly on the initial ocean conditions imposed on the model. Assimilating TAO/TRITON ocean data has been shown by e.g., Ji and Leetmaa (1997) to be greatly superior to initializing with only wind data or even XBT data; in the latter case the increased spatial and temporal coverage provided by the TAO array was the reason. The improvements in SST anomaly correlation coefficients and rms errors were between 25-30% for the region 170°-120°W and 5°N-5°S. Smith and Meyers (1996) suggest XBT and tropical mooring data are mostly complementary but note the critical, unique role of mooring data in the equatorial region

Surface winds are used both to evaluate and improve operational wind analyses and to test the impact of such analyses on ocean models and initializations. This is particularly important in the tropics, where winds from atmospheric forecast models, which are typically used to initiate ocean and coupled ocean-atmosphere models (e.g., Menkes et al., 1998), tend to be less realistic (Reynolds, see material at OOPC/TMBN URL given on p. 3). As an example, the NCEP operational wind analyses were shown to be too weak along the equator prior to 1996.

Salinity data, where available, are also important in the tropics because the observed salinity changes are equivalent to several cm in terms of sea level anomalies. Although salinity measurements have been taken on TAO moorings since 1987 (an almost continuous record since 1988 exists for 0°, 165°E), this has not been a routine operation. Instead, support has been pieced together from a variety of sources over the years in an attempt to develop a coherent measurement strategy. At present, over 20 moorings are instrumented for real-time salinity in the Pacific, including the TRITON moorings and those along 95°E. These limited data have allowed researchers to estimate "pseudo-salinities" from the structure of the temperature field. The relationships will be of great use once Argo floats are available (Ji, see material at OOPC/TMBN URL; Delcroix and McPhaden, 2002). In contrast, all PIRATA moorings measure salinity at four vertical levels, including the surface.

From experience in real-time climate prediction at the International Research Institute (IRI) at Columbia University, the case can be made very clearly that variability associated with all the tropical ocean basins is important to producing good global climate forecasts (Zebiak, see material at OOPC/TMBN URL). Thus, the moored arrays are uniquely valuable in the near-equatorial regions. Outside this narrow latitude band the case is less clear, and other systems might suffice. Within the tropics, the situation is dependent on the magnitude and importance of local variability. While the Pacific is certainly most important at present, the similarities between the Pacific and Atlantic suggest that sustained observations in the Atlantic, as per PIRATA, will be equally useful. Because the Indian Ocean is so important for climate variability in southeast

Asia, India and East Africa, any increase in observations here will likely also have real value. However, the lack of general knowledge of the tropical Indian Ocean precludes any quantification of operational utility at present.

In general, users find the rapid dissemination of data, their high quality, and the provision of subsurface temperature data to be particularly valuable for both initiating models used in ENSO prediction and for comparing with the output of hindcast and forecast model runs. In some cases the data are not used directly, but are withheld from models and compared to model outputs during analyses.

3.3 WEATHER PREDICTION

The three major data products from the tropical mooring arrays are SST, surface winds, and upper ocean temperature profiles. The first two in particular are useful for weather forecasting, and many National Weather Prediction (NWP) centers are making use of these data. As an example, the Australian National Meteorological and Oceanographic Center makes use of the meteorological and sea temperature data from TAO/TRITON for both forecasts and for initiating ocean models. For their purposes, the data are better spaced than data from either VOS lines or floats, are available much more frequently, and are of routinely high quality.

Such feelings are shared by other groups, for example the U.K. Meteorological Office (UKMO), who use the data both for weather forecasting and short-term (5-day) climate forecasts. The Indian Meteorological Department similarly incorporates data from their moored buoy network in day-to-day weather forecasting, particularly for predicting storm surges associated with tropical cyclones in the Bay of Bengal and the Arabian Sea.

Until the advent of satellite-borne scatterometers, particularly Quikscat, reliable real-time wind data from the tropical Pacific were not otherwise available, and the real-time data from the moorings are still used to define any bias in the reported satellite data (see section 3.4). Given that, at present, no “operational” scatterometer missions are either in place or planned, the importance of these data is likely to remain critical for a considerable time to come, possibly forever.

3.4 CALIBRATION OF SATELLITE OBSERVATIONS AND USE FOR ANCILLARY MEASUREMENTS

With the advent of satellite observations for parameters such as SST, sea surface height, surface winds, rainfall and possibly even salinity, it might be thought that the need for tropical moored arrays is declining. However, experience seems to suggest otherwise. SST measurements by satellite have been taken routinely since the early 1970s, yet there seems to be no call to stop sampling this parameter from the arrays in the Pacific and Atlantic. There are two main reasons for this. The first is that the data from the moorings are acquired continuously (see Table 1), apart from occasions when the instruments or the transmission system fail. In contrast, satellite data are collected only when the satellite passes directly overhead, and to give global coverage, this means that the satellite’s orbit must precess. Data recovery from a given point therefore depends on this rate of precession. With the present system of AVHRR on polar orbiting satellites, this normally means twice a day provided the sky is clear. Microwave sensors do not suffer from the cloud problem, although they are affected by rain, but the number of data matches remains relatively small at present. This will increase as the newer EOS satellites are launched.

The second reason for continuing in situ sampling is that mooring instruments are calibrated on a routine basis (at least annually). They thus serve as a prime source of data against which to calibrate the measurements derived from satellites. A particular example of the need for such calibration occurred in 1982 during the eruption of El Chichon (Reynolds et al., 1989) and the 1991 eruption of Mount Pinatubo (Reynolds, 1993). Both eruptions produced large quantities of aerosols, which reached the stratosphere and caused strong negative biases (> 1°C) in the estimated SSTs for over six months. In the former case, although in situ data were available, they were ignored by operational agencies because they were thought to be in error!

At present, tropical moored buoys provide about 25% of the data used by FNMOC to calibrate satellite SST in the tropics. However, satellite SST retrieval accuracy statistics show no significant differences for measurements derived with or without the mooring data. This probably reflects the relative maturity of satellite SST algorithms. As far as satellite-derived SST is concerned, the present Pacific mooring array is almost certainly over-sampling (Reynolds, see material at OOPC/TMBN URL given on p. 3). However, instruments do break down and not all the buoys planned for the arrays in the Pacific or Atlantic are presently in place, so a modicum of over-sampling is called for. Moreover, for higher frequency products, such as those from the GODAE High-Resolution SST Pilot Project (http://www.bom.gov.au/GODAE/HiResSST/), access to high-frequency SST and surface wind and flux fields is a critical element of the strategy.

The need for better in situ calibration becomes more important with other measurements. For example, sea level estimates from GEOSAT and TOPEX/POSEIDON were validated using TAO data (Picaut, see material at OOPC/TMBN URL), this study also identified strong diurnal signals due to internal tides. SST and sea surface height are generally consistent over fairly large areas, but variability in wind or precipitation tends to be on the local scale, so that more ground truthing is required to reduce errors in these measurements. For such measurements, there will likely never be enough moorings for data calibration purposes, but wind measurements from the TAO/TRITON array are being used to calibrate ERS-1 and ERS-2 scatterometer data. There is, of course, a tendency to assume that the in situ data have better absolute accuracy than the satellite data at all times; this is not the case, but the routine calibration of the mooring instruments is a way of determining any bias.

A salinity mission (Aquarius) is being planned with a potential launch date of 2006. If funded, this mission will produce a monthly, global, sea surface salinity map at 100 km resolution and 0.2 accuracy. Although state-of-the art, the satellite data will be affected by heavy rain events in the tropics, thus the ground truth data from moorings will remain vital throughout the life of the instrument (probably three years).

The tropical moorings also provide a means of obtaining ancillary data at a relatively low cost. Operational groups value the arrays because they provide the surface meteorological data at high resolution and can also support current meters or other instruments. During the TOGA-COARE program, for instance, additional moorings were set west of the date line, and additional temperature, salinity and rain rate sensors were deployed on several of these. Other moorings were equipped with enhanced instrumentation for surface flux measurements (Cronin and McPhaden, 1997). Similar enhanced instrumentation, including atmospheric pressure, short- and long-wave radiation, is also in place on moorings along 95°W as part of EPIC (Cronin et al., 2002).

Are there additional instruments that could be deployed on the present tropical moorings to improve our knowledge of this region and make the moorings more cost-effective? An expansion of the salinity measurements is certainly an important potential area for enhancement; the history of such measurements has been given in section 3.2. There is much interest in improving our knowledge of the oceanic carbon cycle, and new instruments are being developed to monitor not only pCO_2, but possibly also nutrients and other chemical species, within the next five years (Dickey et al., 1998; 2001; Tokar and Dickey, 2000). NOAA recently sponsored a workshop to discuss how best to improve our knowledge of the ocean carbon system (Bender et al., 2002).

One of the main recommendations from this workshop was that pCO_2 sensors be deployed on the TAO/TRITON moorings to monitor changes in the carbon dioxide flux within the equatorial Pacific. This has already been done on a small scale since 1996, and the moorings at 2°S, 170°W and 0°, 155°W are presently equipped with such sensors (Chavez et al., 1998).

Another area where the TAO moorings have been used for ancillary measurements is bio-optics. Experience with such sensors goes back to 1992 (e.g., Foley et al., 1997; Chavez et al., 1998; 1999). If these and other chemical sensors can be made small and robust enough to survive continuous operation for a year on a mooring, they will provide extremely important new information on biogeochemical cycling and its relation to large-scale ocean variability.

Finally, it must not be forgotten that ships are required to service the moorings. These servicing voyages provide additional opportunities for scientists to collect hydrographic and other data in an extremely cost-effective manner. One recent example of this work is the paper by Johnson et al. (2001). Other examples of projects currently using the servicing cruises are given in the contribution by McPhaden in the background documentation (see material at OOPC/TMBN URL given on p. 3).

3.5 OTHER USES

3.5.1 Operational oceanography

The U.K. Met Office (UKMO) uses tropical mooring data routinely in their ocean analysis and prediction systems. The UKMO has found that, with regard to the provision of operational ocean analyses for seasonal climate outlooks, the data from the arrays are very important. Through assimilation of those data into ocean analyses in near-real-time, the coupled global circulation model prediction system has more accurate initial ocean information in the tropical (particularly Pacific) regions that strongly influence the forecasts. The mooring data also provide the forecasters with observational monitoring information about behavior in recent months which aids the interpretation of the forecasts. The moorings further provide validation data needed for assessments of forecast reliability and skill with regard to upper ocean structure, and provide the observations needed to assess and improve the performance of the ocean global circulation model component of the prediction system.

The U.S. Fleet Numerical Meteorology and Oceanography Center (FNMOC) also uses the mooring data for operational purposes, assimilating about four reports per day from both TAO and PIRATA moorings. Data are received within a few hours of measurement, and are routinely of high quality. Mooring data constitute about 25% of the data used to calibrate satellite SST retrievals in the tropics. Because of the good satellite coverage, it is perhaps not surprising that withholding the TAO and PIRATA SST measurements has little impact on the final SST analysis product for either global (NOGAPS) or regional (COAMPS) models, as reported also by the U.S. National Climate Data Center. Similar studies on the impact of wind data have not been made, but it is believed that the data from the arrays are very valuable, as they fill critical data voids in both the Atlantic and Pacific Oceans. Subsurface temperature data from the arrays in both Atlantic and Pacific are similarly critical for operational ocean products, particularly in the Atlantic. The fact that the buoys can provide co-located meteorological and subsurface data makes them particularly important, as for large regions of both the tropical Atlantic and Pacific, no other data are available during any given month (Figs 7, 8). This aspect of data uniqueness is discussed further in section 4.2.

Other groups (e.g., the French MERCATOR project), are also using the TAO/TRITON and PIRATA data in similar ways because of the high data quality and the length of the available records. All these groups consider that the continuity, high temporal resolution, and reliability of the data available from the tropical moored buoy arrays is critical for operational activities (see background documentation, also material at OOPC/TMBN URL given on p. 3).

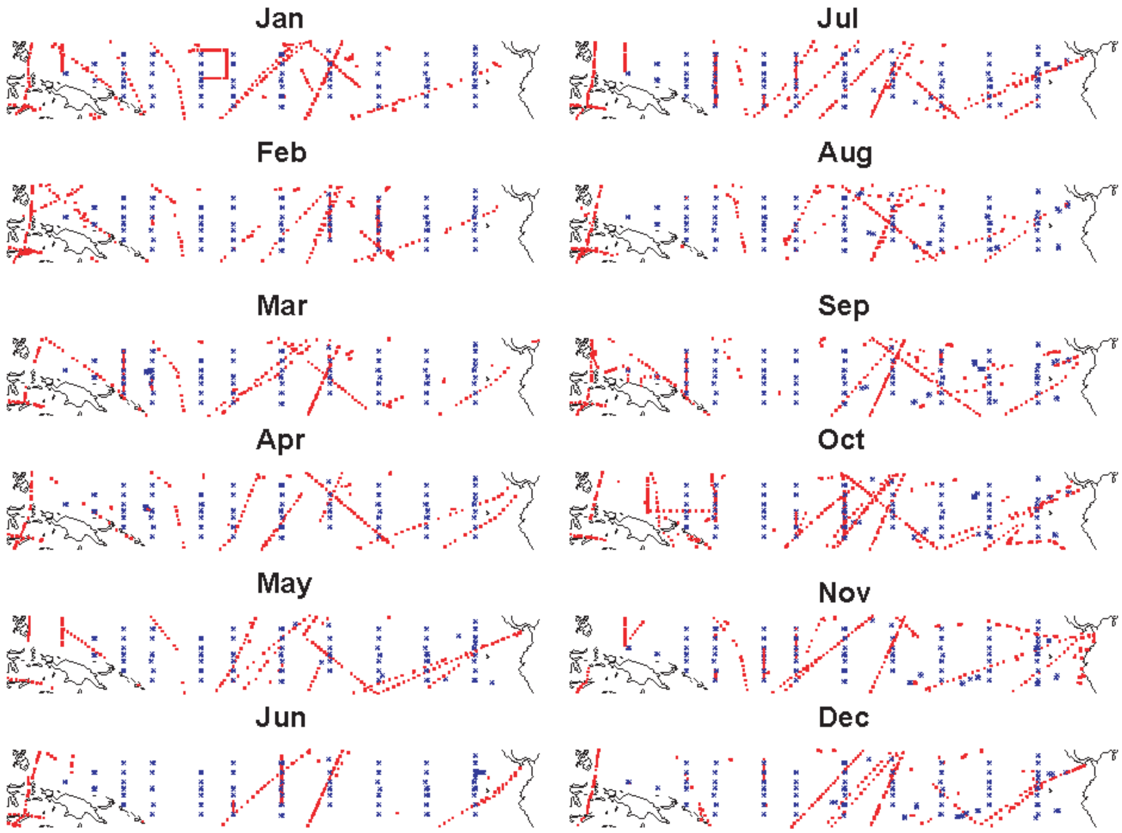

Figure 7. Geographic locations of TAO/TRITON arrays (blue) and other equivalent sources of subsurface thermal observations (red) during 2000.

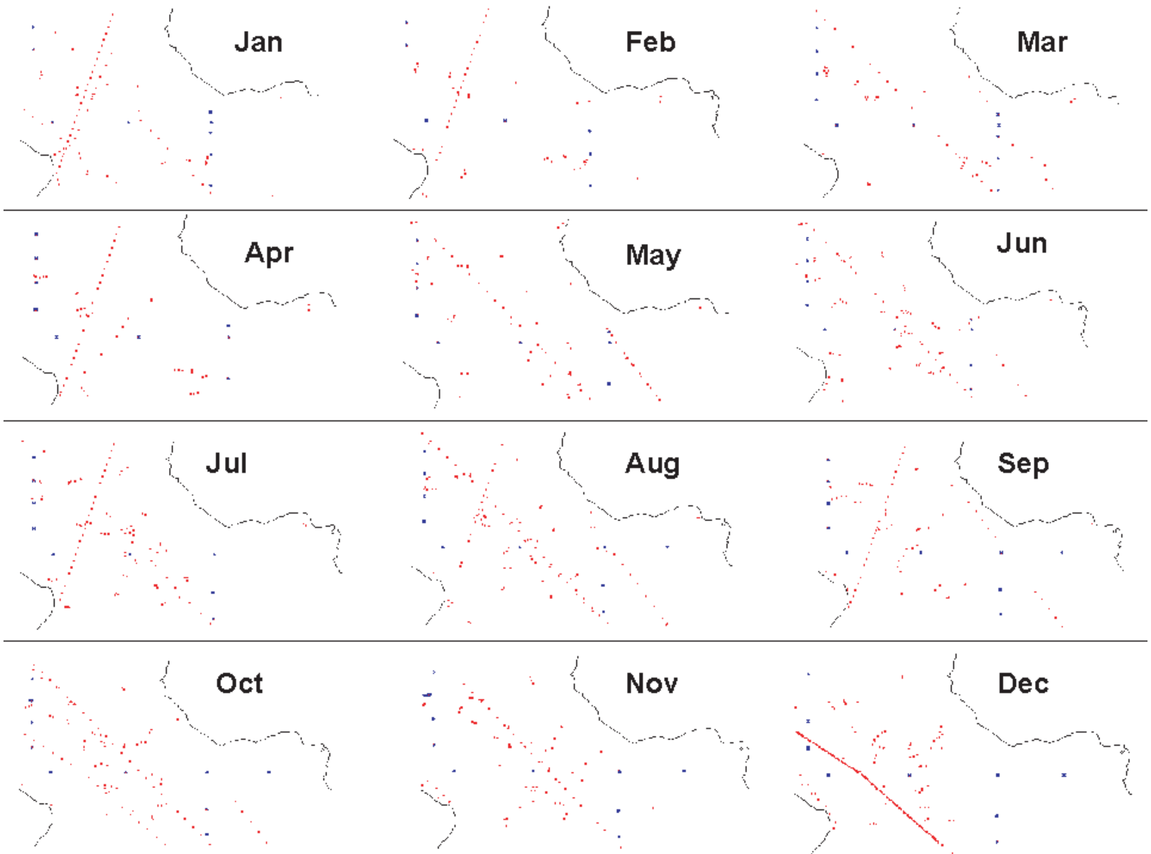

Figure 8. Geographic locations of PIRATA arrays (blue) and other sources of equivalent subsurface thermal observations (red) during 2000.

3.5.2 Model initiation/verification (all scales)
According to Delecluse (see material at OOPC/TMBN URL given on p. 3) "A numerical ocean model can provide an "exhaustive" description of the ocean's evolution. However, this picture accumulates errors from the forcing fields, numerical approximations, inaccurate parameterizations, and the initial conditions within the space-time filter chosen for the integration." It is thus necessary to evaluate the accuracy of the model output. Such estimates as the "mean state" and its variability can be compared with the in situ data from the tropical mooring arrays and provide a valuable source of verification information.

As an example, Fig. 9 (from Vialard et al., 2001) shows a comparison between model results and in situ temperature data along the equator. While the agreement is generally good, as shown by the generally high correlations and relatively small rms differences in the lower panel, it is clear that the model thermocline is not sharp enough and that the discrepancies between model and data increase towards the east of the basin. Similarly, the correlations in the surface at 147°E and 165°E are relatively low. This may be a function of the low variability in this region of the western Pacific, and the greater importance of heat fluxes in driving SST variability (which suggests that the model surface flux formulation is inadequate). Elsewhere, the vertically homogeneous correlations suggest that there is a consistent model bias and that variability is underestimated. Similar results are available for salinity and current velocities.

A decade of relatively dense information from the TAO array has allowed detailed analysis of upper Pacific Ocean behavior in models (e.g., as described above and by the UKMO and many other groups), which has benefited model development. In fact, several researchers believe that mooring array data are more valuable for model validation and development than for operational prediction. Systematic errors are visible also in models of other tropical oceans, and any extension of mooring arrays to these areas is expected to help model development also. The European Union is supporting a major collaborative project (called DEMETER) to develop further the production and application of coupled global circulation model-based seasonal forecasts, and will also support a related project (called ENACT) on the development of ocean data assimilation systems with specific application to seasonal prediction systems. Both of these projects will make extensive use of the moored array observational datasets.

3.5.3. Other activities
During the 1990s, many nations have been making plans for an operational Global Ocean Observing System (GOOS), as part of a Global Climate Observing System (GCOS)–see OOSDP (1995) for the main aspects of the system and GOOS (1999) for operational requirements. While much of the discussion is related to better climate (especially ENSO and similar variability) or weather predictions, four additional components relate to coastal zone management, safety of life at sea, living marine resources, and the health of the ocean. While not mentioned specifically in GOOS documents, aspects of national security for coastal states are also important uses for which buoy data are vital. Moored buoy systems can help with all of these aspects. For example, moorings have long been used to provide data on currents and wave height for coastal areas from the North Sea to southern Africa. Velocity data from 0°, 165°E were used by the Republic of Nauru to help locate a lost fishing vessel. Such data are useful also for fisheries research, especially when coupled with meteorological and other data of the sort obtainable from the tropical arrays. Moored data buoys around the coast of India, soon to be expanded, are providing data of use for offshore oil exploration, fisheries management, port activities, and, because of the importance of the monsoons, to agricultural production. The data are used not only in real-time; they are important also for seasonal and annual forecasts. In this regard, the European Union's DEMETER forecasting project has specific links to agricultural and health applications, and the results will be used also in evaluating the benefits of seasonal forecasts for other uses. It is anticipated that such ancillary spinoff projects will become more important as new ways are found of interpreting the available data.

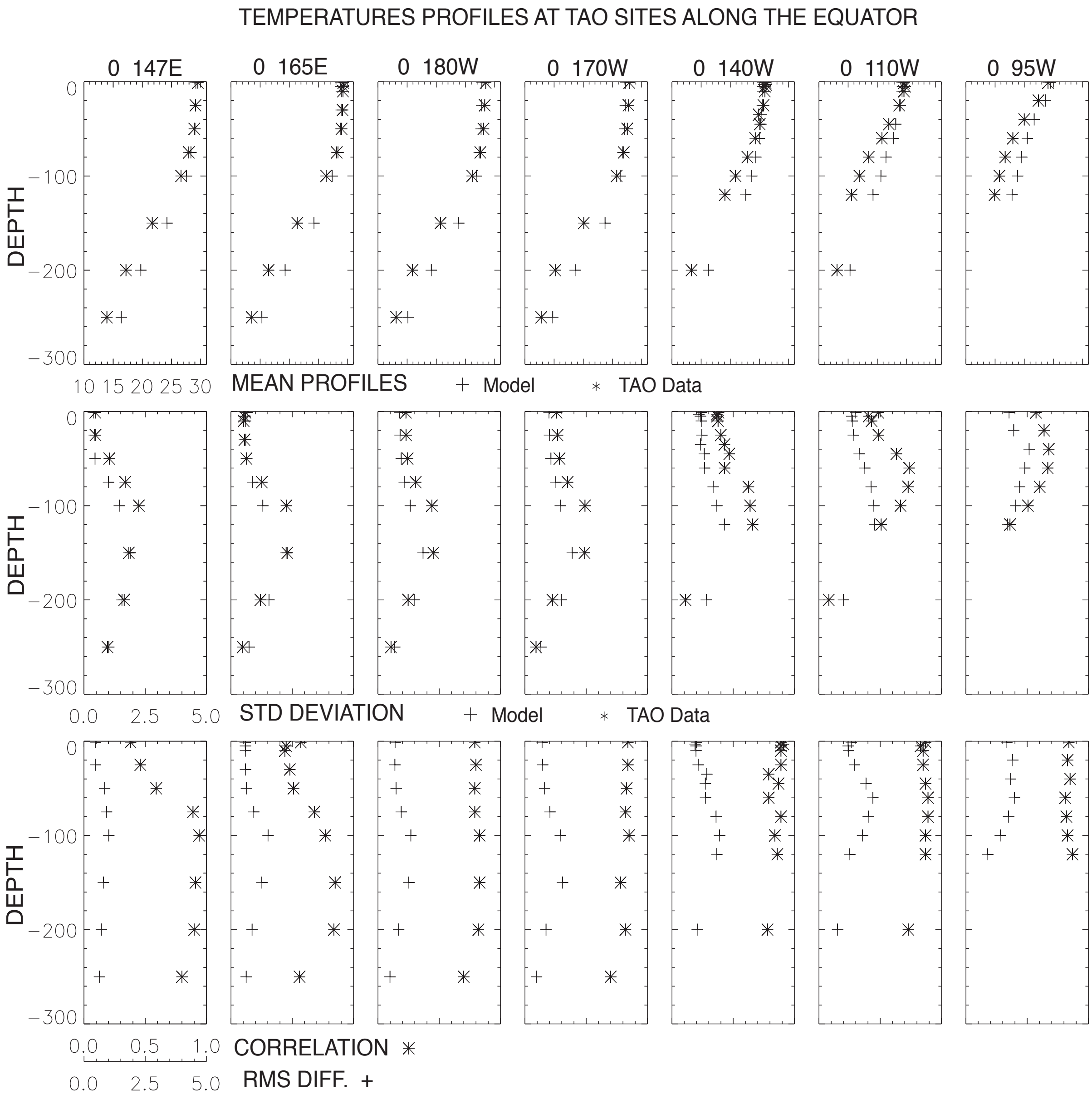

Figure 9. Comparison between model and TAO in situ temperatures along the equator at 147 E, 165 E, 180 , 170 W, 140 W, 110 W, and 95 W. The upper panel shows the mean profiles, the middle panel the standard deviation, and the lower panel the rms difference and correlation (from Vialard et al., 2001).

While not part of the moorings per se, much additional scientific work is carried out during the servicing cruises, as mentioned in section 3.4. A brief description of a dozen projects is available (see material at OOPC/TMBN URL given on p. 3). One specific spinoff from the program is the hydrographic data collected during the servicing cruises. To date, data have been collected along 259 sections since 1991, of which over half have ADCP data. Nominal spacing is 1-degree of latitude, with sampling to 1000 m depth. These data augment the information on the structure of the upper water layers.

4. ARRAY PERFORMANCE

For both scientific and operational reasons, there is clearly a need for an ocean observation system. Any such system must include not only the observing platforms, but also quality assurance, data analysis, and data products. The initial plans for sampling in the tropical Pacific were set almost 20 years ago, during the early 1980s, although sampling rates and coverage have since increased considerably (Tables 1, 2). The question to be asked now is whether this sampling strategy remains useful, or whether it should be changed, and if so, how. This section considers the performance of the array from several aspects. Each aspect includes some general comments that refer to the individual contributions, as well as a series of bullet points that served to guide discussion at the Workshop.

4.1 DATA STREAMS

It is clear from the results discussed in section 3 that the tropical moored arrays in the Pacific, and, to a lesser extent in the Atlantic, are collecting systematic, reliable, high-quality data sets in a timely manner. The number of publications that have used the Pacific data (currently 30-50 per year–the Atlantic array has not yet had sufficient time to generate many papers) also suggests that the arrays are situated in regions of high importance and relevance for scientific and operational applications.

Each data stream has its particular strengths and weaknesses. These are discussed separately below. The questions posed by the bullet points are not all answered in this section although they are stated for completeness; the most important are revisited in section 6.

4.1.1 *Surface winds and fluxes*

Surface winds and other meteorological data from the tropical moored buoy network are valued for both research purposes and for operational weather prediction, particularly as a source of high-quality, unbiased measurements. For research, however, the surface heat and moisture fluxes are gaining in importance. The OOPC and the NWP community are collaborating in establishing a set of surface reference sites for fluxes so that model parameterizations and data assimilation systems can be improved (the SURFA project). The oceanographic community for its part is endeavoring to deliver high-quality estimates of fluxes in real time, while the NWP community is developing metrics that will ensure attention to fluxes becomes part of the routine assessment. The co-location of the different measurements was considered to be a major advantage of mooring arrays. For surface fluxes in the tropical Pacific, SURFA has determined that the most important requirement is to improve measurements along the equator, where four moorings (Longitudes 110°W, 140°W, 180°W and 165°E) have been suggested. As a second priority, it was suggested that moorings along the EPIC line at 95°W be instrumented to the same standard, although problems with vandalism here will likely impact on any decision (see Section 4.4).

Although wind measurements provided the initial rationale for establishing the TAO array, and were a major reason for the present array design, the present ready availability of scatterometer data suggests their importance may decrease in future. However, while there is presently some redundancy in wind measurements, operational scatterometers are still at least four years away and their long-term continuation is not assured. The NWP centers are concerned about their ability to provide reliable estimates of surface wind without mooring data, which, moreover, are used to calibrate/validate satellite data. This use makes mooring winds irreplaceable in the near term, at least.

One specific item relates to the TRITON wind data. At present, TRITON winds are given relative to magnetic north, rather than true north. This imparts a bias of 5-7° in the western Pacific. It is anticipated that this error will be corrected early in 2002.[2]

For other surface marine data there is less that is distinctive about TAO data sets, though clearly the tropics remain a region that is difficult for atmospheric models. The availability of integrated marine measurements is of major importance for surface flux studies and for developing planetary boundary layer parameterizations. The high-resolution temporal sampling is considered to be particularly important for this work.

Regarding surface winds and other flux measurements, the key issues for the Review were:

- Does the original over-riding rationale based on surface winds still hold today? If so, what level of priority do we attach to these data compared with other surface and subsurface data?
- Is the current quality adequate for the range of purposes to which the data are put?
- How important is it that the datasets are integrated (collocated wind, SST, etc.)?
- If there are to be rationalizations and/or enhancements driven by consideration of surface winds, what should they be?
- Are the requirements for the different basins effectively the same or are there different requirements and priorities?
- The rationale for surface flux measurements of heat and moisture is perhaps stronger today than it was during TOGA. How much stronger, and what are the implications for sampling?
- Are the suite of marine measurements appropriate and of the right quality? What are the highest priority enhancements to consider?

4.1.2 *Surface temperature*

Despite the availability of SST measurements from satellites (AVHRR, AATSR, microwave and geostationary), and evidence that the mooring data have very little effect on basin-wide estimates (see information provided by Reynolds and Stockdale at the OOPC/TMBN URL), there was no support for stopping SST sampling from tropical moorings. It was felt that sampling SST as part of a suite of co-located data far outweighed the relatively small cost savings that might result. Given the ongoing discussion about the future of combined SST products, and the lack of agreement on the relative merits of skin and bulk SST measurements, the meeting had no recommendations on this point.

The key questions in this section were:

- In the light of emerging methods for SST products (combined geostationary, AVHRR and microwave based methods), and the distinction between bulk and skin SST, are there changes required of the tropical moorings? Are they appropriate Dedicated Data Sites as described in the GODAE SST project (GODAE, 2001)?

4.1.3 *Sea surface salinity*

Assuming that the SMOS and Aquarius missions to measure salinity by satellite are accepted, additional in situ salinity data will be required for calibration purposes. While such data, which are also useful for descriptive and diagnostic purposes (Delcroix and Picaut, 1998; Delcroix and McPhaden, 2002) may be obtained from drifters and Argo floats, it should be noted that the OOSDP Implementation Plan (OOSDP, 1995) strongly recommended augmenting such

[2] According to Y. Kuroda (pers. comm.) the necessary software changes were made in April 2002.

measurements on TAO/TRITON moorings. Such measurements have, in fact, been made over many years on TAO moorings, albeit discontinuously in both space and time.

4.1.4 *Subsurface temperature and salinity*

The rationale for subsurface T/S measurements is clear and strong, since they provide details of changes in water mass structure that cannot otherwise be obtained easily–CTD and XBT/XCTD data are far less frequent and more widely distributed. The meeting agreed that additional vertical sampling within the mixed layer would be advantageous, particularly in the tropical Atlantic, where it was recommended that extra measurements be taken at 10 m depth. This enhanced sampling (including salinity) should also be initiated at the heat flux sites on the equator in the Pacific. Regarding subsurface salinity measurements in general, although the moorings provide an attractive platform, the balance between cost and effectiveness is not so clear as for temperature. This is because the instruments are less stable and reliable; the scientific interest is strong but not overwhelmingly so; the operational impact remains largely unknown; and there are complex sampling issues. There is no reason to reduce subsurface salinity sampling where this is presently done, but fewer enhancements were called for, and the highest priority was assigned to flux measurement sites.

While altimetric measurements and Argo provide alternate sources of subsurface T and S data with potentially a considerable amount of redundancy, the temporal sampling and fixed-point character of the tropical mooring arrays is unique. Once Argo data become available and there is a sufficient mix of data from other platforms, it will be necessary to examine the complementarity of data from moorings, Argo and ships of opportunity, similar to the Smith and Meyers (1996) study for VOS and mooring data, to determine the validity of the prevailing assumption that Argo floats can provide the necessary information.

Regarding subsurface temperature and salinity measurements, the main issues were:

- Has the subsurface temperature requirement taken over as the principal rationale for tropical moorings? Might the answers be different for the different oceans?
- Is the present data stream meeting requirements? Are there any clear and obvious areas of redundancy? What are the priorities for enhancement?
- Does the presence of altimetry and Argo effect the strategy? Does the improvement in models affect the strategy?
- Where does salinity lie in terms of priorities? Are the existing data streams of adequate quality? Where are the regional priorities?

4.1.5. *Ocean currents*

Ocean currents are an important component of the tropical mooring data stream. Their importance is, if anything, increasing as a result of GODAE and operational oceanography, and there was considerable support for increasing velocity measurements on tropical moorings. Augmentation of current sampling is particularly important near the surface since the shallowest sampling for this parameter occurs at about 30 m depth. It is recommended that a limited number of equatorial moorings (most likely those used for heat flux measurements), be instrumented to monitor current velocities within the top 5-10 m of the water column. Adding extra point current meters and/or ADCPs on other moorings, particularly along the equator (to monitor the local divergence and the Equatorial Undercurrent) or to monitor low latitude western boundary currents, also found support, despite the considerable financial implications and the present unavailability of data from moored ADCPs in real time. It was acknowledged that such measurements are available from research vessels during servicing cruises, as well as from a combination of drifters, altimetry, and Ekman calculations. Thus, the extension of in situ current measurements to these regions is of lower priority at present.

Issues concerning ocean current measurements included:

- Where does the collection of ocean current data fall within the list of priorities?

- Do the requirements vary from basin to basin, and within basins? For example, the Indian Ocean is likely to place higher premiums on ocean current data than deeper temperature data.
- How important is real-time transmission?
- Has the presence of altimeters enhanced or lessened the importance attached to current measurements?

4.2 SAMPLING STRATEGY

Here, differences in sampling for different fields/variables are ignored, and the section concentrates on the overall strategy. The issues include:

- Has our knowledge of spatial scales of variability for the Pacific, Atlantic and Indian Oceans changed to an extent that would affect the present approaches?
- Does additional sampling from, for example, scatterometers, altimeters or Argo suggest a change is needed? Does the revamped SOOP strategy have any effect?
- Do the changing scientific and/or applied priorities have any implications for the horizontal sampling strategy?
- Does the Review wish to reiterate the importance attached to high temporal sampling, or is the tropical moorings' role in process studies likely to decrease?
- How important are the off-equatorial moorings? How high on the list of possible expansions should extra extra-tropical moorings be placed? Or is this where we start to rationalize?
- Can there be less zonal resolution? Is the wind sampling the main determinant or is it now subsurface structure?
- How damaging are the gaps in records? Are models any use in filling in these gaps? At what point does a record become fatally compromised?
- Is the vertical sampling rate and extent still appropriate? Is vertical sampling more important than adding additional sensors?
- Do all sites need to be continuing and long-term, or should consideration be given to a more dynamic sampling approach?

The sampling strategy for the Pacific has proven extremely effective; without TAO data, many studies of climate variability in the tropical Pacific would have been hopelessly compromised. The original sampling strategy was based on work by Harrison and others and revolved around the spatial and temporal variability of tropical winds. The present horizontal sampling is only barely adequate by those standards–indeed, U.S. CLIVAR plans for the Pacific Basin Extended Climate Study (PBECS; see U.S. CLIVAR, 2000) suggest that considerably closer horizontal spacing is needed to describe the different fields. Some relevant scales, over which sampling will be needed for the 15-year lifetime of the program, are:

- air-sea fluxes (heat, water, momentum) δx 300 km, δt 12 h;
- near-surface currents δx 300 km, δt 10 days; and
- T/S profiles δx 300 km, δt 10 days, δz 5 m to 1500 m depth.

In the equatorial wave guide, meridional separation becomes important:

- T/S profiles δx 1000 km, δy 100 km, δt 5 days, δz 5 m to 500 m depth;
- velocity measurements δx 1000 km, δy 100 km, δt 5 days.

Despite the apparent discrepancy between the array spacing and "ideal requirements," it appears that the data from both the TAO/TRITON array and the PIRATA array have considerable impact on operational forecasts. Cummings (see OOPC/TMBN URL) calculated relative weightings for mooring data, as compared to non-mooring data, and showed that including the mooring data increased the constraints on the model forecast by about 50% or more over large areas in both oceans. The effect was larger in the Atlantic (Fig. 10) than in the Pacific, mainly because there are few other subsurface data in this region.

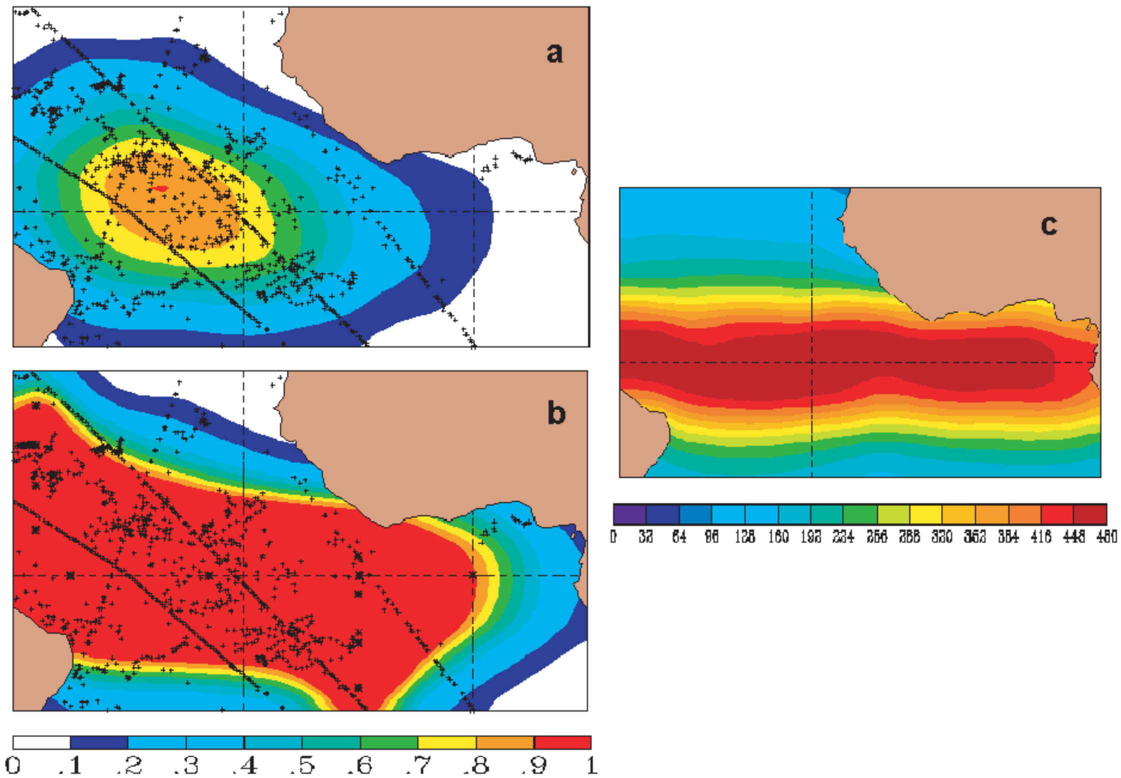

Figure 10. Impact of tropical moored buoy observations on analysis weights in the PIRATA area during 2000. (a) analysis weights computed with PIRATA mooring data denied; (b) analysis weights computed with PIRATA mooring data included; (c) correlation length scales (km) used in the analysis, defined as twice the Rossby radius deformation scales reported by Chelton et al. (1998). Non-mooring data locations are marked with a (+) and mooring locations are marked with a (*).

There was general agreement that the region within five degrees of the equator is the most important for all measurements, and that measurements at 8° N or S were likely of lesser importance, except perhaps in the Indian Ocean. In this ocean, there is a major seasonal current reversal south of India (5°-8°N) , while the role of the South Equatorial Current (near 10°S) in climate variability remains uncertain. It was argued that outside the equatorial wave guide, or regions where high-resolution flux measurements are needed, a combination of Argo floats, drifters and satellites could perform equally well as moorings. Although there was some discussion of the possibility of enhancing the meridional spacing close to the equator, possibly by exchanging moorings at 8°N or 8°S for sites at 1°N and 1°S, the scientific justification for this was less compelling than maintaining the status quo. In the Atlantic Ocean, we do not yet have the necessary data to decide whether the present spacing is suitable for either scientific or operational use.

A possibility for the future is to extend the arrays at their western and eastern ends into the low latitude western boundary currents and the eastern boundary upwelling regions. The latter is presently being investigated along the South American coast by Chile, Ecuador and Peru. However, given the present prevalence of vandalism at moorings at both ends of the TAO/TRITON array, it is likely that this would have considerable cost implications. Mooring vandalism may be reduced, but probably not eliminated, by education of the fishing communities, more frequent refurbishment of the moorings, re-engineering efforts, or by omitting certain measurements (e.g., the anemometers which are the most frequently vandalized components). All these methods are presently being tried, but the vandalism continues to the detriment of the science.

The strategy for the Atlantic sampling was different to the Pacific, though not greatly so. Both the SST and surface wind patterns and the signal to noise ratio are different, making sampling in the Atlantic possibly more difficult. The dominance of monsoon and intraseasonal signals in the Indian ocean suggests the sampling strategy there should be different yet again, principally because of the relatively greater importance attached to higher-frequency variability.

Despite the apparent mismatch between TAO/TRITON horizontal sampling scales and those given above, the temporal sampling frequency is unlikely to be a problem. High-frequency temporal sampling has always been a requirement which the present strategy seems to have more than met, and the present situation exceeds the PBECS requirements by a considerable margin. As pointed out by Kessler et al. (1996), the high temporal sampling rates on the moorings reduce considerably any errors due to time-induced sampling biases.

Vertical sampling is mostly dictated by the semi-permanent thermal structure of the ocean but it is compromised at times by the high variability at the depth of the thermocline (in these cases the vertical separation between instruments on the same mooring is too great). The vertical extent of sampling seems to have been adequate for most applications, but, as pointed out in section 4.1, closer near-surface vertical spacing is recommended for certain parameters at certain moorings in both the Pacific and Atlantic arrays.

4.3 DATA AVAILABILITY AND EXCHANGE

There is a general satisfaction with the way that data from the tropical mooring arrays are being distributed among researchers. To quote R. Reynolds (see material at OOPC/TMBN URL given on p. 3)

> "Data from the TAO array is a model of how oceanographic data should be shared. The TAO data set was one of the first sets that were made available not only to operational users via the GTS but all interested users via the Internet. Thus, forecasters could get the

real time data while other users, who could tolerate short delays, could get quality-controlled data."

Most users are happy with access to the data via the GTS and the web pages. Data from individual moorings can be found and downloaded easily, while the later incorporation of delayed-mode data increases the total data stream considerably. There are, however, some perceived problems relating to metadata and the lack of analysis products, interpolated data sets, and the like. The first of these may result from individual researchers not being aware of the latest changes made at the TAO website, which has been extensively revised during the past year and displays clearly the available data (including gaps) and other technical information such as sensors, sampling rates, quality control, and mooring design.

Regarding the lack of analysis products, interpolated data, and "best guess" cleaned up data sets, PMEL has never been mandated nor funded to supply these items, even though such products could be useful to the community, particularly for model initiation. Many other groups are charged specifically with producing blended analysis products, and many examples of their work are given in section 3 and the papers by McPhaden et al. (1998, 2001). Given their limited funding support, which has no allowance for inflation, it seems unnecessary and counter-productive to require PMEL to move from their forte of providing the basic data for such activities.

At present, the salinity data from the TRITON array are not being made available because of worries over data quality. Given the critical nature of these data from the western Pacific, their early release would be of great value to the community, and it is recommended that JAMSTEC release these data as soon as practicably possible.

4.4 DATA RETURN

A simple starting point for determining array performance is perhaps the rate of data return. In Figs. 11 and 12 respectively are shown the recent real-time data recovery rates (as percentages) from all TAO buoys deployed in the Pacific and the PIRATA buoys in the Atlantic. The numbers are calculated by summing for each variable the number of days per year that a daily average was available, and dividing by the product of the number of days it should have been available (generally close to 365, allowing for deployment and recovery) and the number of variables. The numbers corresponding to each set of variables are given in Tables 7 and 8. As these refer to real-time data, if there are problems with data transmission, then the delayed-mode data availability may be greater than shown. These statistics on data return would seem to be a model that could usefully be accepted by other networks. This section is broken down into the following three topics:

- Data loss through instrumental failures;
- Data loss through transmission failures; and
- Overall data return rates.

4.4.1 Data loss through instrument failures

Tables 7 and 8 show that the data returns from individual sensors vary considerably from one mooring to another. For example, the overall data return from wind sensors in the TAO array is only 85%, compared to 92-93% for air temperature and relative humidity (for the PIRATA moorings there is <60% wind data return). Such discrepancies are generally related to vandalism, as the wind sensors are highly visible and high up on the moorings.

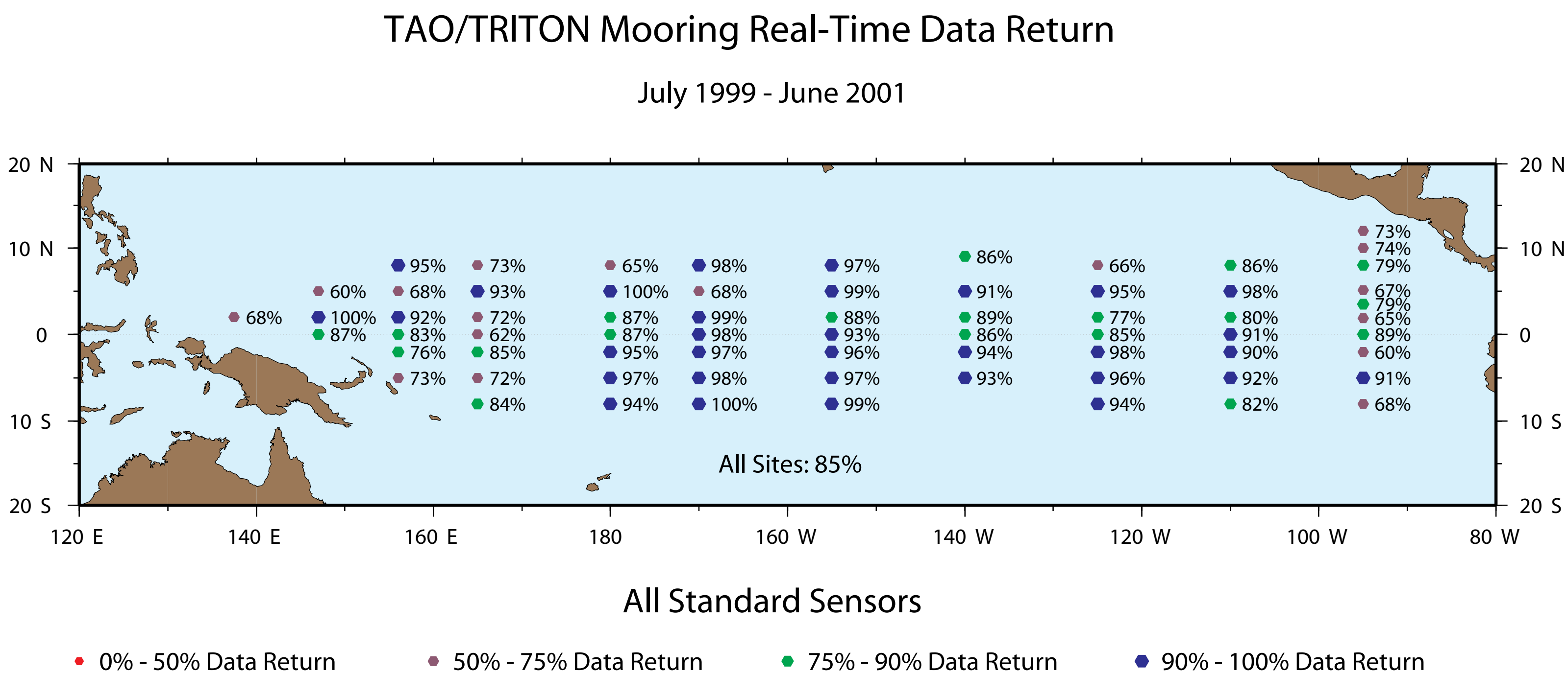

Figure 11. Real-time data recovery rate for TAO ATLAS moorings east of 160 E for the period May 1999-September 2000 (figure supplied by M. McPhaden).

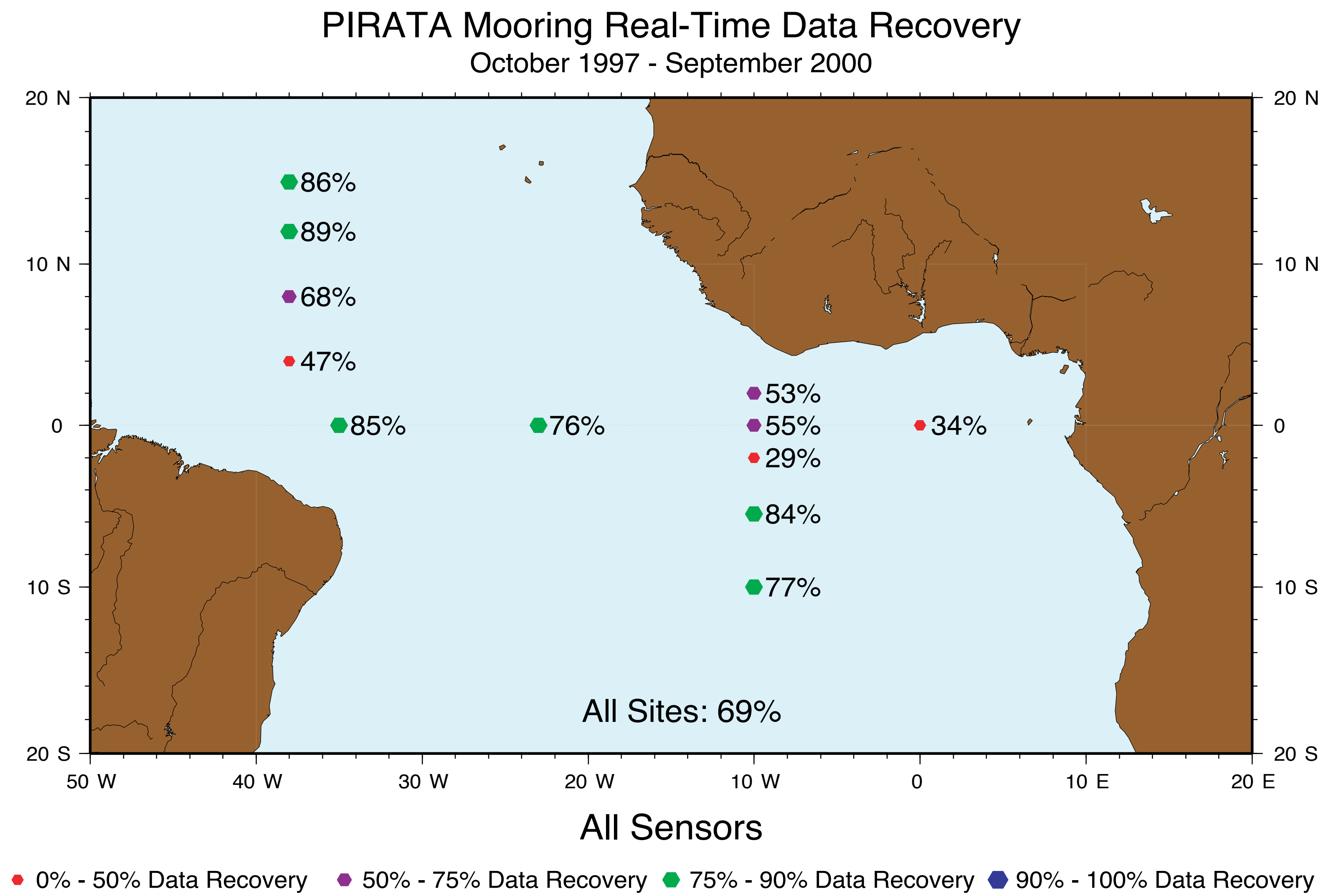

Figure 12. Real-time data recovery rate for PIRATA ATLAS moorings for the period October 1997-September 2000 (figure supplied by M. McPhaden).

Table 7. Real-time data returns for Pacific moorings, July 1999-June 2001. All numbers in percentages. * denotes all samples with less than 80% real-time data return; ** less than 65%.

Mooring position	Air temp.	Rel. humidity	SST	Sub-surface temp.	Wind	Combined
2°N, 137°E	56**	56**	70*	71*	56**	68*
5°N, 147°E	73*	73*	73*	56**	73*	60**
2°N, 147°E	100	100	100	100	100	100
0°N, 147°E	82	82	90	88	77	87
8°N, 156°E	84	85	100	97	85	95
5°N, 156°E	100	100	82	58**	100	68*
2°N, 156°E	79*	80	100	95	74*	92
0°N, 156°E	74*	75*	85	84	85	83
2°S, 156°E	53**	53**	84	82	53**	76*
5°S, 156°E	92	96	96	65*	96	73*
8°N, 165°E	80	82	80	71*	64**	73*
5°N, 165°E	99	100	79*	93	90	93
2°N, 165°E	85	85	81	68*	76*	72*
0°N, 165°E	70*	70*	50**	62**	55**	62**
2°S, 165°E	78*	79*	77*	89	63**	85
5°S, 165°E	90	90	90	67*	73*	72*
8°S, 165°E	99	100	46**	86	74*	84
8°N, 180°E	71*	63**	72*	67*	36**	65*
5°N, 180°E	100	100	100	100	100	100
2°N, 180°E	96	96	93	84	96	87
0°N, 180°E	89	88	89	87	80	87
2°S, 180°E	68*	98	97	96	98	95
5°S, 180°E	98	97	98	98	97	97
8°s, 180°E	100	99	100	92	99	94
8°N, 170°W	91	92	100	99	100	98
5°N, 170°W	74*	100	53**	63**	96	68*
2°N, 170°W	99	99	98	99	99	99
0°N, 170°W	100	100	100	97	100	98
2°S, 170°W	93	94	98	98	94	97
5°S, 170°W	99	100	76*	99	100	98
8°S, 170°W	100	100	100	100	100	100
8°N, 155°W	99	100	99	96	94	97
5°N, 155°W	99	98	99	99	98	99
2°N, 155°W	100	100	75*	86	100	88
0°N, 155°W	96	98	97	91	99	93
2°S, 155°W	98	98	98	97	82	96
5°S, 155°W	99	99	99	96	99	97
8°S, 155°W	99	100	99	99	98	99
9°N, 140°W	93	94	90	83	90	86
5°N, 140°W	99	98	94	89	98	91
2°N, 140°W	97	97	97	90	47**	89
0°N, 140°W	100	100	100	80	100	86
2°S, 140°W	99	100	99	93	88	94
5°S, 140°W	99	86	99	92	99	93

Table 7. Real-time data returns for Pacific moorings, July 1999-June 2001. (continued)

Mooring position	**Air temp.**	**Rel. humidity**	**SST**	**Sub-surface temp.**	**Wind**	**Combined**
8°N, 125°W	94	94	86	59**	61**	66*
5°N, 125°W	84	86	99	99	69*	95
2°N, 125°W	100	99	100	68*	99	77*
0°N, 125°W	99	100	99	79*	100	85
2°S, 125°W	99	99	99	98	99	98
5°S, 125°W	97	97	97	96	97	96
8°S, 125°W	87	87	99	95	99	94
8°N, 110°W	92	93	77*	88	68*	86
5°N, 110°W	99	100	99	99	83	98
2°N, 110°W	85	84	91	79	67*	80
0°N, 110°W	95	95	95	90	85	91
2*S, 110°W	93	93	93	90	81	90
5*S, 110°W	98	99	98	90	99	92
8°S, 110°W	99	99	99	76*	92	82
12°N, 95°W	89	90	89	71*	43**	73*
10°N, 95°W	98	99	86	66*	97	74*
8°N, 95°W	82	82	77*	78*	82	79*
5°N, 95°W	81	81	81	64**	59**	67*
3°N, 95°W	95	96	72*	77*	68*	79*
2°N, 95°W	70*	71*	70*	64**	61**	65*
0°N, 95°W	93	93	82	91	77*	89
2°S, 95°W	62**	63**	48**	65*	20**	60**
5°S, 95°W	95	97	91	89	92	91
8°S, 95°W	90	93	77*	59**	93	68*
Total	**90**	**91**	**88**	**84**	**83**	**85**

Table 8. Real-time data return (in percent) from PIRATA moorings October 1997-September 2000. * denotes less than 80% data return, ** less than 65%.

Mooring position	Wind	Air temp.	Rel. humidity	SST	SSS	Rainfall	Radiation	Sub-surface temp	Combined
15°N, 38°W	79*	93	85	99	50**	100	98	90	86
12°N, 38°W	100	99	99	96	32**	99	97	89	89
8°N, 38°W	67*	74*	76*	76*	56**	74*	62**	72*	68*
4°N, 38°W	53**	20*	53**	53**	53**	53**	52**	46**	47**
0°N, 35°W	62**	80	99	98	93	88	96	84	85
0°, 23°W	40**	87	88	87	88	90	87	77*	76*
2°N, 10°W	36**	54**	54**	54**	54**	55**	54**	53**	53**
0°N, 10°W	26**	62**	63**	55**	86	41**	56**	51**	55**
2°S, 10°W	37**	39**	39**	39**	0**	36**	34**	31**	29**
6°S, 10°W	55**	97	100	97	95	55**	93	88	84
10°S, 10°W	84	99	100	60**	32**	32**	97	83	77*
0°N, 0°W	22**	48**	26**	48**	48**	19**	47**	34**	34**
Total	**55**	**71**	**74**	**72**	**57**	**62**	**73**	**67**	**65**

Issues relating to instrumentation include:
- Are there variables for which loss of data is more damaging than others? Are there cases where instrument redundancy might be an effective strategy?
- For the specific case of salinity, is there any guidance that can be provided by the review? What reliability is required?
- In view of the importance attached to integrated and co-located data sets for basic research and for surface flux estimates, is there any specific strategy that should be recommended?

There was a general consensus that all the data were of value, thus no data set was considered more important than others. However, as discussed earlier, the subsurface temperature, salinity, and velocity data are apparently becoming more important than previously. Salinity is a particularly challenging measurement to make for year-long surface mooring deployments. Both ATLAS and TRITON moorings use Seabird conductivity cells which, though electronically stable, are subject to drift because of either biofouling or cell scouring (Freitag et al., 1999; IOC, 2001). These drifts are most severe in the surface layer and typically diminish with depth. Uncorrected by post-calibration, they can be as large as several hundredths to more than 0.1 psu.

Argo floats will hopefully report salinity data accurate to better than 0.01, since these spend only short times at the surface and are therefore much less subject to fouling (Roemmich et al., 2001). It may be, therefore, that the Argo float data can be used as another way to calibrate salinity data from the mooring arrays, but careful comparisons between these data sets is needed.

4.4.2 Data loss through transmission failures

Most tropical moorings rely on Service ARGOS for telecommunication and the (now) JCOMM data networks for real-time communication. The Data Buoy Cooperation Panel has the lead for negotiating agreements. Of the many considerable impacts of the TAO array during TOGA, the transition to real-time data transmission and hence real-time access to Pacific Ocean data has perhaps had the most profound effect. However, there have been occasional problems with this strategy, mostly beyond the control of individual laboratories.

Issues relating to this aspect include:
- What is the level of data drop out that can be attributed to the telecommunication strategy? Is it at a level that should be a first order concern?
- Does the review believe the present strategy is cost-effective or should we argue for development of alternative systems?
- Are there losses of information (e.g., precision, temporal resolution) that could be avoided?
- How critical is timeliness (the difference between observation time and final reception at laboratories and operational centers) and is it an issue at present in terms of data received?

The present rate of data loss in transfer from Argos to the GTS and in transmission through the GTS is around 10-15%. Almost all the missing data are recovered during mooring servicing, and thus enter the data stream as part of the delayed-mode data set. However, given that one of the major uses of the mooring data is for initiating near-real-time forecast models, this GTS loss is not acceptable. The proposed relaunch of the Iridium system of satellites for two-way data transmission may provide an alternative means of collecting data from the moorings, although the GTS link remains a potential problem area. Experimenting with Iridium transceivers is encouraged, although the necessary redesign of ATLAS hardware, software and data processing protocols will have major cost implications.

The question of data timeliness has been addressed by scientists at FNMOC (Cummings, see OOPC/TMBN URL given on p.3). To be of use for FNMOC's data assimilation system, the data must be received within 24 hours of measurement, and pass internal quality control checks. The timeliness of data received during 2000 from both the TAO/TRITON and PIRATA arrays was compared with that from other sources. TAO/TRITON data make up about 90% of all Pacific data received, and the mean time elapsing prior to receipt is about 6-9 hours, well within the time window. While data from other sources are usually received within 3-6 hours, the difference is not critical and the high reliability and volume of the TAO/TRITON data makes them very valuable. The difference in time before receipt is attributed to the fact that satellite overpasses of the moorings are essentially fixed.

In the Atlantic, PIRATA data provide approximately 40% of the data stream. The mean time from measurement to receipt of the data at Monterey is between 11-13 hours, again well within the time window. This compares with mean times in the 25-65 hour range for alternative data sources. There was no sense that data degradation was occurring during transmission other than the 10-15% GTS dropout rate discussed above. Additionally, the acceptance rate of data (relative to the standard quality control checks used at FMNOC) was consistently above 98%, apart from the 150-200 m depth range in the Pacific, and the 120-140 m depth range in the Atlantic, where it was reduced to 95-96%. It is thought that the higher discard rate at these levels relates to a lack of knowledge of the climatology in regions of rapidly changing T/S characteristics, rather than inherent inaccuracies in the data themselves (Cummings, see OOPC/TMBN URL).

4.4.3 Overall data return rates

For both the TAO/TRITON and PIRATA arrays, the data recovery rate is variable, depending on location. Vandalism, presumably by fishermen, is a major problem for both arrays. This occurs particularly along 95°W and in the western Pacific (Fig. 11) and in the Gulf of Guinea (Fig. 12). In the TRITON area, nine of ten moorings showed signs of vandalism during 2000-2001 (IOC, 2001). Efforts to reduce vandalism, such as distributing informational brochures to national fishing agencies, industry representatives and local boat owners, or making presentations at international meetings of fisheries scientists and managers, continue, but it is unclear if these methods are effective. In addition to vandalism, several moorings have broken free from their anchors and drifted away from their deployment sites. For example, 17 ATLAS moorings have been affected in this way between October 1997 and September 2000, of which nine were lost completely and eight partially recovered. At least two of the present PIRATA array moorings have also drifted. While statistics on data returns from the Indian EEZ moorings are not available, these moorings too are prone to vandalism and few sites have so far returned continuous data for more than one year (Premkumar, see OOPC/TMBN URL).

Issues that relate to this topic include:

- What is the minimum data return that is acceptable for the tropical mooring arrays? Can there be different data return rates in each ocean? Has the critical point been reached in the eastern Atlantic or elsewhere that renders particular moorings essentially useless?
- Will additional shiptime, e.g., a dedicated ship such as the NOR-50 proposal from France, and more frequent servicing, reduce losses due to mooring and/or instrument failure?
- Does the present data loss that can be attributed to too infrequent servicing constitute a major issue insofar as the data are used for climate studies?
- Are the direct and indirect costs justified from a scientific impact perspective? (In the extreme case, some records may become useless for climate work. Conversely, for ocean and weather prediction, the effect is probably no greater than the loss of a single point for some time.)

While it is generally true that any data are better than no data, a key function of these arrays is to provide real-time, rapid warning of changes in the ocean climate, which are needed by forecast centers. Thus, breaks in data transmission, for whatever reason, are more critical than e.g., losses of hydrographic data along a section or of position data from PALACE floats, where there are generally recent data from around the sampling point that can perhaps be substituted to describe the large-scale fields. A possible cutoff for acceptable data return rates in the Pacific is suggested as 80%.

In the Atlantic, data returns are much worse (Table 8). Sensor and mooring technologies are the same in the Pacific and Atlantic, but while Pacific moorings are serviced every six months, PIRATA moorings are only serviced on a 12-month basis. Thus, any mooring losses from PIRATA will likely have a more serious effect on the overall data return from the Atlantic than in the Pacific. As an example, a PIRATA mooring along 35°W was lost four months after deployment. With a 12-month service schedule, this meant eight months of data were lost (33% data return for that year). In the Pacific, the mooring would have been replaced on a regularly-scheduled six-monthly visit and, assuming no further loss, would have produced 10 months of data in all (83% data return). It is accepted that the Atlantic moorings are part of a pilot project, thus a lower data return may be allowable initially. However, setting acceptable rates as low as 65% or 50% still means that a high percentage of individual returns fail, with combined moorings totals also falling below the cutoff. It has been estimated that six-monthly servicing might lead to a 10-14% improvement in data return in the Atlantic. A decision on ship-time is needed now if it is to be implemented for the operational phase around 2005. Two PIRATA mooring sites (2°N, 10°W and 2°S, 10°W) have already been decommissioned, and without some means of reducing the vandalism, the value of continuing the PIRATA array in its present form must be in doubt.

Engineering changes are being made on an ongoing basis to moorings in an attempt to reduce the incidence of vandalism and mooring drift in all three oceans. While this has a small effect, it is unlikely to completely solve the problem. Additional service support (as discussed by Servain et al., 2001), will also reduce data loss, but this has potentially large financial implications, and unlike in the Pacific, dedicated shiptime is presently not available for such work in the Atlantic. A final possibility, if all else fails, would be to reduce the scope of the moorings by removing the more obvious instruments such as anemometers or other meteorological sensors, but this would require a careful assessment of scientific and operational tradeoffs on an individual mooring basis.

4.5 SCIENTIFIC AND SOCIO-ECONOMIC FACTORS

Apart from the bare statistics of data return rates, what can we say about the use of the data to researchers and forecasters? Information from contributors suggests that the data from the tropical mooring arrays have been extremely useful and continue to play an important role in basic science, particularly as regards the seasonal-to-interannual variability of the tropical oceans. Additionally, the data are used intensely for climate prediction, ocean analysis and prediction, and weather prediction (see section 3). ENSO prediction remains the primary application for the data, with many different institutions using the data for this purpose. Although at present the impact of Pacific data is clearly greater than that of Atlantic data, the impact of the latter continues to increase. This was brought out in the meeting on tropical Atlantic variability, held in Paris immediately prior to the Seattle review (Carton, pers. comm.).

The clearest evidence of the importance of the TAO/TRITON array was seen during the buildup of the 1997-98 El Niño, when measurements from the array clearly showed a warming in the upper 400 m in the western Pacific early in 1997, associated with zonal wind anomalies (Fig. 13). This contradicted results from the “benchmark” model used for forecasting, (that of Cane et al., 1986), which was forecasting cooling, but agreed with sea level data from TOPEX/POSEIDON (McPhaden et al., 2001). While other models predicted better the temperature changes during the warm-up phase, none apparently captured both the onset and the later rapid decline of the El Niño (at 0°, 125°W the SST dropped 8°C in 30 days during May-June 1998).

Regarding the operational impact of the tropical moored arrays, the meeting was asked to consider questions such as the following:

- Few applications use anywhere near the full mooring data set (this is true for satellite data also). Does this have any implications for the evolution of the array?

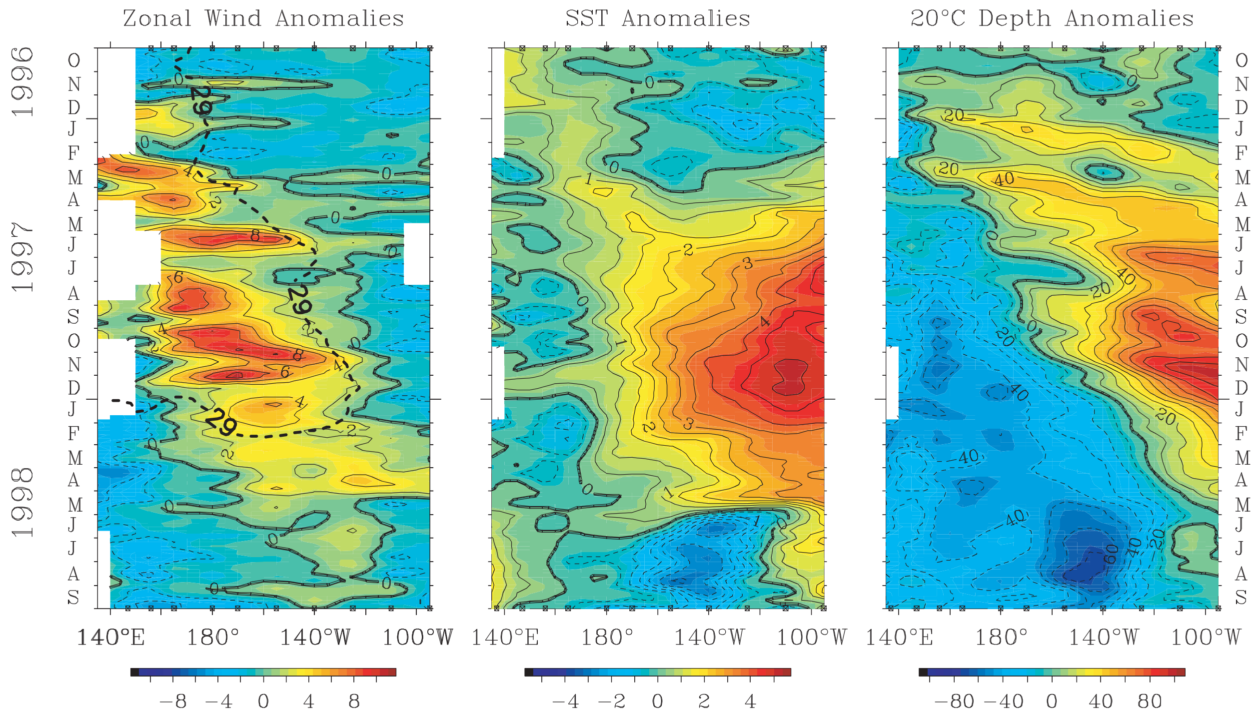

Figure 13. Anomalies in surface zonal wind (in m·s-1, left), sea surface temperature (in °C, middle), and 20°C isotherm depth (in m, right) from October 1996 to September 1998. Analyses are based on 5-day averages of moored time series data between 2°N–2°S from the Tropical Atmosphere Ocean (TAO) Array. Heavy dashed line in the left panel is for the 29°C isotherm through early 1998. White areas indicate missing data.

- Are there any issues related to quality for any of the operational applications?
- Is the importance of good wind data diminishing?
- Has the importance attached to heat and moisture flux data increased?
- What and where are the next most important climate priorities?
- For operational oceanography, ocean currents presently have heightened priority and salinity likely will become more important, irrespective of whether satellite measurements of this parameter become available. Are other parameters likely to be of importance?
- For weather prediction, it would seem the focus has shifted from use of mooring wind data for model initialization to use of mooring marine data to improve and tune planetary boundary layer parameterizations and to understand short-term (diurnal to several day) variability. Is this true?

Several of these items have been considered in earlier parts of section 4 (e.g., the relative importance of wind and flux data). There was little concern about either the quality of the data or the fact that most users used only some of the available data sets–although all data sets are used. In contrast, there was a strong belief that the co-location of many different sample streams was a positive advantage. The addition of other sensors to the moorings is discussed further in section 3.4. Generally, there was consensus that the moorings continue to be a remarkable source of high-quality data for operational use.

The scientific impact seems equally important. Users of satellite data find the mooring data invaluable for calibrating remotely-sensed data, although the use of the mooring data varies depending on parameter (section 3.4). Thus SST data are relatively unimportant as a result of the maturity of the algorithms used to convert the satellite measurements, whereas wind and meteorological data are more critical, and salinity and current measurements are seen as becoming more important in future.

There is no question that tropical mooring data have been influential in climate research over recent years (section 3) and that this influence will continue through CLIVAR. There does not seem to have been any major shift in emphasis post-TOGA, except for increased interest in salinity and more enthusiasm for the Indian Ocean. The rate at which papers based on TAO data are published is a direct testament to their influence and scientific utility, and a strong endorsement of the data management policy. Recent moves to use the mooring arrays as sites for testing new sensors suggest that the arrays will continue to be important for many years to come.

The meeting was asked to consider the following:
- Given the scientific objectives of CLIVAR and other research efforts, and the strategy being developed for PBECS, what changes, if any, should we recommend for the tropical mooring array in the Pacific? Should we favor enhanced instrumentation? Expanded implementation in the eastern Pacific? More using of resources for process studies?
- Given the scientific objectives of CLIVAR and the conclusions from the September 2001 Atlantic Variability Workshop, what are the strengths and weaknesses of the approach in the Atlantic?
- Given the conclusions of the Workshop on Sustained Observations for Climate of the Indian Ocean (Perth, November 2000), where does the review feel the strongest scientific impact will be for the Indian Ocean?

The meeting clearly supported sustaining the status quo in the Pacific. There was considerable discussion on expanding the arrays both zonally and into new areas in the low-latitude western boundary currents and the eastern upwelling regions, but it was recognized that such additions would be very vulnerable to vandalism. However, Chile, Ecuador and Peru are proposing potential extensions along the South American coast, and the meeting supported the idea of such a consortium as a way of raising new funds for this work. A similar proposal for the Indian Ocean (I-MAP, 2001) was also supported, again with the suggestion that a consortium of local countries, perhaps with some support from the U.S., be encouraged to work together to augment current plans of India and Japan. The aim here should be to improve knowledge of the air-sea fluxes, currents, and temperature and salinity structure through the mixed and barrier layers. It was accepted that a staged implementation of any Indian Ocean array was desirable, and that vandalism would likely prove as problematic here as elsewhere.

In the Atlantic, there are several proposals for local enhancements of the PIRATA array. Again, these are dependent on logistics (e.g., ship availability) and the acquisition of new funds. The workshop assumed that the PIRATA array would continue at least through 2005, when the Memorandum of Understanding between the U.S., France and Brazil on maintaining the array expires.

As a final effort, it is useful to consider some economic aspects. It has been suggested (Changnon, 1999) that the direct value to Californian consumers and agricultural producers of the advanced warning provided by the array prior to the 1997-98 El Niño was approximately $1 billion. Similarly, it is estimated that the countries of the western Indian Ocean region could save $2 billion annually through strategic planning based on better predictions (I-MAP, 2001), while Australian gains from better knowledge of ENSO-related cooling could total several hundred million dollars (Nicholls, 1985a, b). Other references on this topic are given in OOSDP (1995). Given that the U.S. spends about $10 million a year (including shiptime) on maintaining its portion of the TAO/TRITON array, this suggests a very healthy rate of return on investment.

5. ONGOING EVALUATION AND METRICS

One of the aims of the review of the tropical moored buoy network is determine ways to monitor its performance through the establishment of a set of metrics and through quantitative studies aimed at evaluating the contribution of the mooring array. However, it is recognized that this evaluation cannot be separated completely from the assessment of complementarity with existing or soon to be available observation networks. To date, no such comprehensive assessment regime for the arrays has been put in place, although some comparisons of individual elements have been done.

The methodology that is being proposed here is similar to the Rolling Requirements Review procedure that has been established by the WMO Commission for Basic Systems for its global observing systems contributions. In essence, the procedure puts in place mechanisms that allow for continuing review and assessment even in the presence of changing requirements and/or changed approaches and technologies. In the present case we are proposing four components, two of which we will discuss in more detail:

1. A set of metrics for the tropical mooring network;
2. A set of quantitative studies for assessing the impact of the arrays;
3. A procedure for scientific evaluation against evolving requirements; and
4. A procedure for technical evaluation and assessment.

Part (3) is effectively in place through the OOPC and various scientific panels of CLIVAR. Part (4) is in effect the Tropical Mooring Implementation Panel (TIP) and its associated groups within the Joint Technical Commission for Oceanography and Marine Meteorology. We will now discuss parts (1) and (2) in a little more detail.

Of particular importance to the evaluation process is the fact that the tropical moored arrays, especially the Pacific array, were designed primarily as scientific tools, not as a means of obtaining operational data. There is still considerable discussion within the community as to the relative importance of metrics associated with scientific, operational or monitoring aspects. This issue is not resolved here but metrics are prescribed that will measure in some sense the degree to which data are exercised for these different purposes.

5.1 METRICS

The objective is to put in place a set of metrics (output and/or outcome measures) that continually and routinely provide a measure of the products and impact of the network. Following discussions at the Seattle meeting, a basic set of metrics was agreed that cover the principal aspects of data collection, as well as some means of evaluating the usefulness of the data to scientists. The latter are discussed further in section 5.2. Note that the metrics mostly are directed at the data collection system and do not assess the performance of any particular Center.

Data network metrics:

- The data returns compared with ideal, as done routinely at PMEL, on an annual basis.
- A count of the observations, by variable and/or instrument, collected (this should probably be daily averages but other counts would have utility, e.g. a marine observation in a 6-hourly bin). This is presently being done routinely by PMEL.
- A measure of the average time taken for the data to reach operational centers, or the land-based Internet service, together with a running measure of the data loss. An example of this was the presentation by Cummings (see material at OOPC/TMBN URL given on p.3).
- A running measure of the amount of time between receipt of original data and production of quality control data (this may have other aspects where data are only collected in delayed mode). The rate at which this occurs may vary from one center to another, depending on the requirement, but at FNMOC the quality control procedure is automatic and almost instantaneous.
- A measurement of how the data rate as regards quality. Again according to FNMOC data, the acceptance rate seems greater than 98% for almost all streams. Similarly, as shown by Fig. 14, the wind data are shown to be of higher quality than those received from ships.
- Sampling performance against recommended rates. This does not seem to be a problem at present.
- Measures of the effectiveness of telecommunications. At present, only 85-90% of the data are received routinely at operational centers via the GTS.

Data utility metrics:

- The number of operational centers receiving and using data, together with a measure of how much of the data set is actually used by each. Similar numbers should be kept for scientific data use, but given the free access to the data, it is hard to know how to do this. One measurement that is logged routinely at PMEL is the number of files downloaded (about 10,000 between August 2000 and February 2002).
- The number of scientific papers and reports that depend directly in tropical mooring data. PMEL keeps an archive list that presently contains about 400 refereed publications and over 700 others.
- Comparing surface field data with NWP products (SURFA project), as well as subsurface data with VOS and Argo (when the latter become more plentiful). This is done occasionally by data users (e.g., Wang and McPhaden, 2001), but is not presently being done routinely across a variety of data products.
- Comparing tropical moored buoy array data with operational ocean model fields (an IPRC/GODAE project is being planned that will do this for the equatorial Pacific).
- Comparing tropical moored buoy array fields with satellites and other in situ data at “cross-over” points. This is a major function of the quality control system for satellite data.
- The number of instances of tropical mooring platforms and/or service RVs being used for other scientific purposes. This is being done by PMEL for the TAO array cruises.

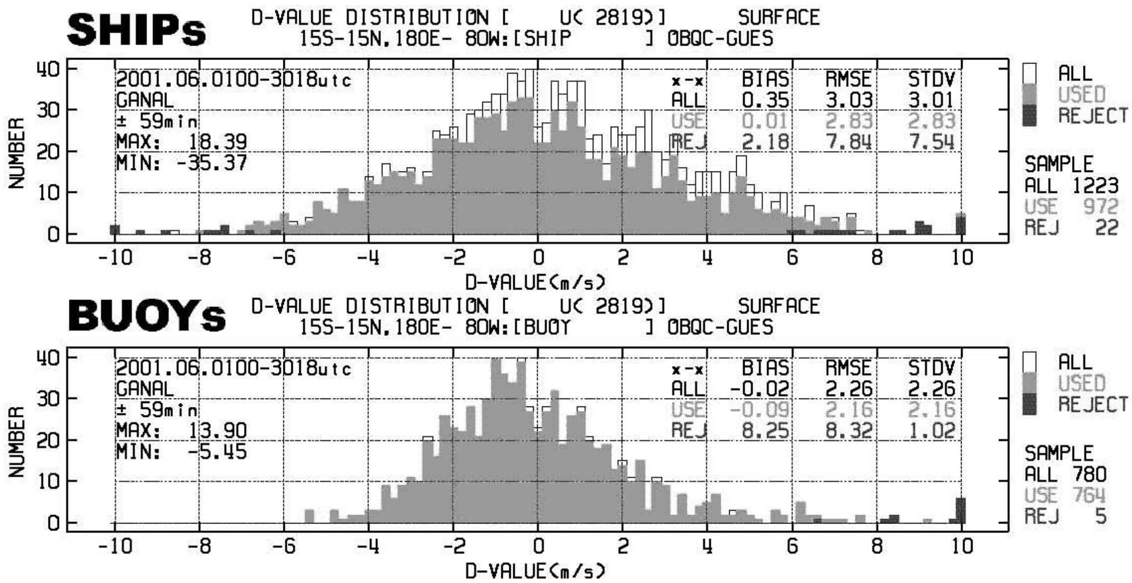

Figure 14. The distribution of the observational departure against the first guess of JMA's operational global analysis. The east-west component of the wind observation data are checked. The upper panel shows the distribution of the ship data while the lower is for the buoy data.

- The impact of ocean data, and in particular that of global tropical moored buoy array data in models of seasonal-to-interannual climate variability including decadal and longer change (e.g., GFDL/ECCO/NCEP).

5.2 EVALUATION AND OBSERVING SYSTEM SENSITIVITY STUDIES

It is important to promote and foster research that evaluates the impact of tropical mooring data for certain applications. Because the data are part of a large and complex observing system, and are mostly processed and used through imperfect models and data assimilation methods, there is no truly objective way of measuring impact. Moreover, depending upon the relative impact attached to certain outcomes (climate prediction versus ocean analysis) and the societal impact, any scientific result will always be ambiguous and subject to further interpretation. These caveats notwithstanding, it is clear that much can be learned from scientific evaluations and model sensitivity studies. It is important to understand how the particular characteristics of the tropical mooring approach are of unique benefit and where there may be redundancy (noting that a level of redundancy is usually desirable). It is also important to understand how different approaches complement each other.

What do the tropical moorings do that other devices cannot? Other than providing surface flux and meteorological data, their main advantages are the provision of velocity profiles in the equatorial zone where narrow, swift currents are important, high-frequency observations, and co-located wind and subsurface temperature measurements. As new instruments are developed, the moorings provide sites for deployment at minimal additional cost (see section 3.4).

Regarding complementarity, the basic meteorological and surface flux data probably cannot be collected on a regular basis in any other way, certainly not at present. For the moment, the same is also true of the subsurface temperature, salinity and current data. However, the launch of the Argo program of profiling floats is imminent. These floats will provide vertical profiles of salinity and temperature on a 10-day cycle, as well as estimates of water movement at depth. It is presently assumed that Argo will not suffice to monitor the equatorial region because the scales of features of interest are too small, the response time to e.g., westerly wind bursts is too short, and because the floats will tend to diverge from the equator. However, the Argo floats will provide about 20,000 profiles annually in the tropical Pacific alone, so there is a need for a hard comparison of the requirements of a total system for measuring internal ocean temperature and salinity that includes the moorings, Argo floats and VOS XBT deployments.

To date there have been few studies to compare the effects of the different sampling systems. Smith and Meyers (1996) compared estimates of the depth variability of the 20° isotherm across the tropical Pacific, using either TAO data, XBT data, or the combined data set, for 10-day periods during 1990-1994. They examined the ability of the data to capture the evolution of equatorial variability, tropical variability between 20°N and 20°S, the relative accuracy of the analyses as given by the rms error variance, and changes in the time series of the areally averaged error and the effective information content per 10-day period. Although limited to the variation in one parameter, the study showed that the TAO and XBT data sets were complementary, with only limited redundancy. As expected, the TAO array provided more information within 5° of the equator, while the XBT data were more effective throughout the tropical region as a whole. Both data sets captured the low-frequency variability within the equatorial band, although the TAO array gives more information on changes in the eastern Pacific (where XBT data are scarcer). On the other hand, in the western Pacific, where slower moving waves and off-equatorial effects are more important, the XBT data become more useful.

The TAO array was being increased considerably during the period examined, and the time-series of the mean areal rms error and the information content of each data set showed this clearly. However, although the TAO array was significantly more important along the equator, during the latter half of the study period the XBT data could still make a substantial contribution to improving the final analysis. However, this study made no attempt to examine the efficiency of either data set in terms of anything other than monitoring/detecting El Niño events.

A second such study (Segschneider et al., 2001) has compared the TAO network, XBTs and altimeter data. The data were all assimilated into the ECMWF HOPE model, and in separate studies one of the data sets was withheld. The set of analyses was then used to initialize a set of coupled ocean-atmosphere model forecast ensembles, which were compared with observed SST data. The results strongly supported the idea that the TAO data were the most important observation system as regards optimum forecasting skill. However, they needed to be combined with either the altimeter or XBT data for best results (which other data set to use depended on region). This result is in contrast to the arguments expressed in Carton et al. (1996) or Masina et al. (2000) in which it was suggested that altimeter data would swamp the mooring data, although they could be used as an independent data set for verification purposes. (Note that the results of Carton et al., 1996 have been challenged by Anderson et al., 2001.)

Other needed comparisons between mooring-derived data and those obtained by satellites include, for example, both SST and wind velocities. Initial studies by NCDC and FNMOC in the U.S. suggest that the moorings either over-sample or add little to the existing operational satellite-derived SST products except in certain special cases such as following volcanic eruptions. It should be noted here that SST is also available from surface drifters, of which a fleet of about 200 is maintained in the tropical Pacific. These tend, however, to diverge near the equator, leaving a gap in sampling, and their sampling rate is considerably lower than from the mooring array. For changes of the magnitude seen following volcanic eruptions, this may not, in fact, be a handicap, but the cost savings from switching from moorings to drifters for SST are very minor.

While satellite wind measurements have not been available for very long, and are still not truly operational, these too need to be compared with the mooring-derived data. The aim is to determine the relevant scales at which ground-truthing must be carried out. A future prospect is a satellite mission to monitor surface salinity (Aquarius and SMOS). While the Aquarius mission will provide a monthly map of sea surface salinity to ± 0.2 on a 100 km grid, the sensor is subject to interference from heavy rain and there will be a continuing need for in situ measurements, including from moorings, for ground truthing purposes. A certain amount of redundancy is needed in all these systems to allow for instrument or data transmission problems, but the questions are, how much, and how do we do such studies?

A primary use of the TAO/TRITON array at present is to provide data for predicting seasonal-to-interannual variability. While the data are used for prediction by global centers, we do not know whether the array is adequate, sub-optimal, optimal, or excessive for predictive purposes. In the past, the expense of undertaking observing system sensitivity experiments with coupled global circulation models has mitigated against such work, but as computing speeds continue to increase and models become more realistic, such activities are more possible. However, due to the limited observational record such results will always be used as guidance rather than as definitive evidence for change.

Anderson et al. (2001) describe several areas where such studies are urgently required. The Review recommended the development of a systematic, coordinated program of modeling and data assimilation to test and evaluate the impact of ocean data in ocean-only and coupled models. GODAE and the CLIVAR WGSIP are collaborating in the evaluation and intercomparison of tropical Pacific analysis products. A targeted program of observing system sensitivity experiments is also required including:

- Investigation of the impact of different platforms, as by Segschneider et al (see above) and Cummings (see OOPC/TMBN URL given on p.3) (e.g., Argo, tropical mooring buoy network, SOOP, satellite);
- Investigation of the impact of different data types (e.g., salinity–Ji et al., 2000);
- Investigation of the impact of different sampling rates;
- Investigation of the impact of surface versus subsurface fields;
- Investigation of the specific impact in climate products

Studies need to be conducted of the (increased) predictability through use of ocean data and/or surface marine data. GODAE is proposing a project to collect statistics from routine data assimilation systems such as at FNMOC (see, for example, Figure 13).

Within the Atlantic, as yet we do not even know whether the array is adequate to meet its scientific objectives, but as PIRATA acquires more data, we shall have a better idea of this. Certainly it appears that the data have a degree of uniqueness that suggests considerable importance, at least for operational centers (Fig. 11).

6. SUMMARY AND CONCLUSIONS

The Workshop was arranged to assess and review the contributions to the global observing system from the tropical moored buoy network. This included also a thorough review of the societal and scientific rationale for having such a network, the establishment of a set of metrics for ongoing evaluation, and recommendations for future developments in the context of continuing global ocean observations for climate studies.

The Workshop agreed that the main societal and scientific issue for the network remained the monitoring, understanding and prediction of seasonal-to-interannual time-scale fluctuations associated with the ENSO cycle. For these purposes, the tropical moored array is a fundamental and critical component (where the definition of "fundamental and critical" is as discussed by OOSDP, 1995) of both GOOS and GCOS. The data streams from the array can, moreover, be prioritized. Some data, such as subsurface temperatures, are absolutely essential. Others, such as wind data for weather prediction models and data for air-sea flux determinations, are important but not unique. A third level of importance applies to contributions that support wider studies; these include such aspects as global SST measurements, the use of the moorings for additional, opportunistic research, or the contribution made to the global ocean observing system. Here, the role of the network is supportive rather than a leading one.

From the comments received during the writing of this report and the discussions at the workshop, it seems clear that there is general agreement on many aspects of the scientific return being provided by tropical mooring arrays. These include:

- The tropical arrays in the Pacific and Atlantic are providing an important set of data for scientific, operational and forecasting uses;
- In situ oceanic meteorology data are far scarcer than those from over the land, so the importance of TAO/TRITON and PIRATA meteorological data is relatively high;
- Because the arrays sample at high frequency, the data do not suffer from the aliasing problem that can affect less frequently sampled measurements;
- The multivariate data sets provided by the mooring arrays are more useful and consequently have higher impact than individual data sets;
- Surface wind data from the moorings are of higher quality than those from ship observations;
- Data delivery from the moorings is faster and more stable than most ship observations;
- Subsurface temperature data from the TAO/TRITON array presently provide the bulk of the coverage from the tropical Pacific and increase substantially the accuracy of ocean analyses in the tropics;

- Without the mooring data it would be impossible to make full use of altimetric data;
- In situ data from the tropics (and elsewhere) are necessary for verifying satellite data;
- Mooring observations are presently essential for monitoring ENSO and making predictions of interannual variability;
- Mooring data are extremely valuable for testing and verifying models; and
- The TAO array is a model of how oceanographic data should be shared, and the web site is particularly useful for displaying data.

While all three tropical oceans are undoubtedly important in modulating global climate, their different physical geography means their roles in heat and mass transport and air-sea interactions differ. They thus pose different scientific questions and require different sampling strategies. In total, the above-listed attributes provide a powerful rationale for maintaining and sustaining the tropical Pacific network and for developing similar sustained systems in the Indian and Atlantic Oceans. Further off the equator, the role and relative importance of fixed moorings providing high-frequency sampling is less clear–the time scales of variability are slower than those within the equatorial wave guide, and there is more spatial variability. Thus, a similar closely-spaced array away from the equator will likely be less relevant and effective.

Because of the accepted importance of the TAO/TRITON array in the Pacific for forecasting El Niño events, the workshop found no compelling scientific justification for changing the present horizontal (zonal or meridional) sampling spacing of this array. It must be stressed, however, that the mere existence of the network cannot guarantee successful predictions of El Niño or other climate phenomena. Such predictions also require well-tuned, accurate models of the evolving ocean-atmosphere system, which have inherent limits to predictability because of the noise and chaotic behavior in the climate system. However, the existence of a reliable network has proven invaluable in dealing with unexpected climate excursions and minimizing associated risks.

Regarding expansion and/or evaluation of the tropical moored arrays, the meeting agreed that this should proceed through an agreed system, with adequate reviews and other controls to ensure that each step makes sense scientifically and economically (based on Nowlin et al., 2001). The suggested procedure is:

- Ideas for new measurements/activities are proposed by scientists;
- Short-term research/pilot experiments are carried out;
- A sustained pilot study is conducted;
- A prolonged observational period is supported, coupled with an evaluation of the program's sustainability;
- Sustained observations continue, with a time period for re-evaluation of about four years.

This methodology needs to be ongoing to ensure the relevance of all data streams. It must also include regular review of the data management functions to ensure the data management centers are maintained and that operational data remain of high enough quality to be useful for climate research in the future.

The three ocean arrays are in different stages of development relative to the above procedure. The TAO/TRITON array in the Pacific Ocean has been built up since the mid-1980s, and has been running as essentially a complete system for almost ten years. It can thus be described as a mature system that is part of a sustained measurement program. The PIRATA array in the Atlantic is considered to be in the fourth stage (prolonged observations during which its sustainability will be examined), although it is intended that it will move to a sustained footing shortly if the present problems with infrastructure and servicing can be overcome. However, with the exception of a few moorings in the far eastern Indian Ocean, the Indian Ocean array presently exists only as a series of planning documents, and funding for the necessary pilot experiments is needed.

There are advocates for both extending the arrays by expanding the zonal coverage in the Pacific and Atlantic, and by increasing meridional coverage by deploying more moorings in the Indian Ocean. In the Pacific, northward expansion is championed particularly by the Japanese, whose main interest lies northwest of the equatorial region, although groups integrating satellite and in situ data (e.g., FNMOC) also need more observations in colder regions and from areas of high ocean energy. In the South Pacific, the Peruvian, Ecuadoran and Chilean oceanographic and meteorological communities are committed to improving their forecast abilities. These countries are trying to establish a series of moorings that will extend operational monitoring from the tropics to the southern part of the continent. This may be done through a consortium of South American states, if the necessary financing can be found. At present, Peru has deployed four moorings, Ecuador is about to deploy two, while Chile is planning to deploy up to 16. The meeting agreed that such additional deployments would not only provide data from an undersampled region of the ocean, but would help promote the concept of an international global ocean observing system.

In the Atlantic, extensions are needed primarily to improve knowledge of the air-sea fluxes and of the seasonal variability in the meridional overturning circulation and its effect on interhemispheric water exchange (COSTA, 2001). Potential regional expansions, which would double the size of the PIRATA array to 20 moorings, have been proposed by Morocco, Brazil, and South Africa/Angola. Again, any such expansion would require new funding and augmentation of the present servicing facilities. The meeting recommended that interested parties establish regional consortia to look for the necessary financial, vessel, and manpower resources.

The expansion to the Indian Ocean, on the other hand, would extend tropical ocean and atmospheric measurements to the monsoon region, which affects over 2 billion people each year. Likely immediate benefits of such an expansion would be better cyclone prediction in Australia, the Bay of Bengal, and the western Indian Ocean. Possible additional benefits include furthering our knowledge of the forcing in the western Indian Ocean that may well contribute to ENSO variability. Information is presently available from moorings and hydrography carried out during WOCE and the JASMINE program to help with planning any such arrays, as described in section 2.5. However, the same problems with logistical support apply here as in the Atlantic Ocean; at present the Japanese plan to service their two Indian Ocean moorings only annually.

Given the present economic situation, it is clear that the only way any of these expansion plans can be implemented is through the development of regional consortia and a program of capacity building. Given also the importance of mooring data to operational agencies, and the often ready availability of Navy ship time for mooring deployment and servicing, the meeting agreed that providing training in maintenance and data management for scientific and technical staff in interested countries was vital. In this regard, it was noted that POGO is considering establishing a series of studentships that could perhaps be used in this way.

A common complaint regarding expanding present arrays or establishing new ones was the high cost of instrumentation. It was felt that this could be reduced if a central organization, such as PMEL, could act to purchase and service all the necessary instrumentation. It was recognized, however, that this would increase the pressure on PMEL, which would also require additional resources if it were to take on this task. In the present financial climate this seems an unlikely possibility.

As regards specific improvements to the present mooring arrays, contributors provided many suggestions as discussed in sections 4 and 5. These included more salinity data, more subsurface current data, and more surface meteorological data for air-sea flux determinations. Atmospheric pressure measurements were also recommended. The surface pressure data (also potentially available from surface drifters) would, in conjunction with buoy- and satellite-derived winds, improve NWP predictions in what is a generally data-void region (see also section 3.1.7).

The community studying fluxes across the air-sea interface has been developing a new program to establish a series of reference sites that describe the characteristics of an ocean region. Assuming that we know the spatial scales over which flux variations occur, it may be possible to use fewer, better instrumented moorings than in the present regular grid to determine large-scale air-sea fluxes. There is considerable momentum at present for establishing a series of such "ocean observatories" and it was felt that the tropical moored arrays could provide a series of sites for this purpose.

The use of salinity and current data is discussed in sections 3.1.4. and 3.1.5. Assuming that the SMOS and Aquarius missions to measure salinity by satellite are accepted, then more in situ salinity data will be required for calibration purposes. Such data may also be obtained by drifters and Argo floats. However, it should be noted that the augmentation of such measurements on TAO/TRITON moorings was strongly recommended in the OOSDP Implementation Plan (OOSDP, 1995), and there is a long track record, albeit discontinuous in space and time, of such measurements on TAO moorings.

The use of the moorings for obtaining ancillary measurements of carbon dioxide species or other biogeochemical data has been discussed in section 3.4. Again there is a track record, which should be expanded in terms of present-day accomplishments and as new techniques become available. However, bandwidth limitations may affect transmission of the real-time biogeochemical data streams. While these data are generally recovered and are included in the delayed-mode data, it was felt that greater throughput, for example by using an alternative data transmission system, would be advantageous.

As regards metrics, the workshop accepted a series of statistical analyses covering both data collection and data utility. The former include such things as counts of observations by variable or instrument on a daily basis; the time taken for the data to reach operational centers; the rate at which quality control procedures are completed; the percentage of the data streams meeting quality control standards; and measures of the effectiveness of data transmission systems. Data utility includes: statistics on the number of operational centers using the data, their scientific output in terms of published papers and reports, and comparisons of data with remotely-sensed (satellite) data and model output. There is also a need for complementarity studies, which use data denial experiments to determine the relative importance of particular data sets. These are all listed below. However, the meeting did not come to any conclusions about what level of data loss would compromise the array fatally. A suggested value for operational purposes was 80% data return for a given mooring.

Specific recommendations resulting from the meeting include:

1. In the Pacific, no changes are presently required as regards mooring positions, but data denial experiments should be conducted to test the redundancy of present sampling rates.
2. In the Atlantic, a core number of moorings (order ~10) should be maintained where they will survive. Additional ship time needs to be made available to ensure more regular servicing.
3. There is presently no array in the Indian Ocean. A consortium of interested parties should be established to arrange for the necessary funding and infrastructure that will allow a pilot array to be deployed and maintained for several years. Funding is also required for the necessary studies on the required sampling scales.
4. Potential expansions have been proposed to both the Pacific and Atlantic arrays. Again, these should be accomplished through the formation of consortia of interested nations and organizations.

5. Mooring arrays should be used to test new sensors and additional measurements should be added as new technology is proved.
6. The present real-time data dropout rate of 10-15% on the GTS is unacceptable. Alternative methods of data transmission will not solve this dropout rate, which is generic to the GTS, but they should be investigated for other reasons such as increasing bandwidth and two-way communications..
7. Four moorings on the equator (at 110°W, 140°W, 180° and 165°E) have been recommended for instrumentation as air-sea flux reference sites. If possible, these sites should have their core measurements augmented to provide better vertical resolution, particularly for the near-surface T/S and velocity fields. Similar augmentation of moorings along 95°W is also recommended. Velocity measurements are also recommended in the low latitude western boundary currents in both the Pacific and Atlantic Oceans.
8. Salinity is seen as becoming more important. Sampling of this parameter should be increased at TAO sites, particularly along the equator and at the eastern edge of the warm pool in the western Pacific.
9. Wind measurements should be maintained on all moorings until operational scatterometers are assured, the necessary ground truthing/redundancy studies are complete, and it can be shown that the value of other moored measurements will not be compromised by deleting winds from the moored data suite.
10. A series of metrics should be taken regularly to determine the effectiveness of the mooring arrays. These should include studies on both data collection and data utility, as listed in section 5.1.
11. A targeted program of observing system sensitivity experiments is required including:
    - Investigation of the impact of different platforms, as by Segschneider et al. (in prep.) and Cummings (see URL) (e.g., Argo, tropical mooring buoy network, SOOP, satellite);
    - Investigation of the impact of different data types (e.g., salinity, Ji et al., 2000);
    - Investigation of the impact of different sampling rates;
    - Investigation of the impact of surface versus subsurface fields;
    - Investigation of the specific impact in climate products
12. Studies need to be conducted of the (increased) predictability found in NWP and other model-derived products through use of ocean data and/or surface marine data.

A final point is the need to assess the true requirements of a sustained observing system in all three oceans, and distinguish between the often conflicting roles of such a system and a scientific research tool. The problems with vandalism (which will be equally pressing for any expanded arrays) suggest that new ways of obtaining data are needed in certain areas. Profiling CTDs on a taut mooring are a possibility here for sub-surface data, but will not permit surface observations. Perhaps drifters with SST and pressure sensors can play a bigger role in such areas. Some researchers have suggested that the tropical Pacific array might even be reduced somewhat in scope, especially if it can be shown that the present array is somewhat redundant. These statements all require that the mooring arrays be integrated properly into any observing system that is proposed, and as stated above, the necessary evaluations have not yet been made that will permit us to make sensible choices. Making such evaluations is probably the most important single contribution to the future.

Finally, however we intend to proceed, the present tropical arrays represent outstanding assets that are providing routine, high quality data of great importance to the present generation of researchers. Before we make any changes to this system, we must be sure that we do not damage or destroy it in the process.

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APPENDIX I:

INTERNATIONAL WORKSHOP FOR REVIEW OF THE TROPICAL MOORED BUOY NETWORK NOAA PACIFIC MARINE ENVIRONMENTAL LABORATORY Seattle, USA Agenda

Monday, September 10

0745	Vans depart the Silver Cloud Inn		
0800	Coffee		
0830	Welcome		E. Bernard
0840	Introductions, Terms of Reference, Agenda		N. Smith

Session I: Rationale and requirements		Chair	N. Smith
0900	Climate forecasting		A. Leetmaa
0920	Climate research		B. Kessler
0940	Climate monitoring, assessments		K. Trenberth
1000	Break		
1030	Summary from the Paris CLIVAR-Atlantic meeting		J. Carton
1100	Discussion of the scientific and operational rationale – establish key points, issues		

Session II: Status of ongoing efforts		Chair	A. Leetmaa
1145	The composite global ocean observing system		N. Smith
1205	Lunch on your own		
1310	TAO		M. McPhaden
1340	TRITON		Y. Kuroda
1410	Pacific extensions, Peru		P. Lagos
1425	Pacific extensions, Chile		R. Nunes
1440	PIRATA		J. Servain
1500	Break		
1530	Indian Ocean plans (SOCIO)		P. Hacker
1550	Indian Ocean extensions		K. Premkumar
1610	Global time series network		R. Weller
1610	Discussion – establish key points, issues		
1715	Adjourn		
1730	Vans depart for the Silver Cloud Inn		
1830	Vans depart the Silver Cloud for reception at Anthony's Home Port		

Tuesday, September 11

0745	Vans depart the Silver Cloud Inn
0800	Coffee

Session III: Complementary networks		Chair	K. Takeuchi
0830	Argo		D. Roemmich
0850	Ship of Opportunity lines		R. Bailey
0910	Drifter array		P. Niiler
0925	Relevant hydrographic measurements		G. Johnson
0940	Sea Level and relevant remote sensing		C. Koblinsky
1000	Break		
1030	Discussion		
Session IV: Additional requirements		Chair	D. Battisti
1100	Short-range ocean forecasting		J. Cummings
1125	Medium range weather and climate forecasting		T. Stockdale
1150	SST analysis		D. Reynolds
1210	Lunch on your own		
1310	Ocean circulation		F. Schott
1330	Satellite validation		J. Picaut
1350	Carbon monitoring		D. Feely
1410	Climate impacts – African case		M. Jury
1430	Discussion – implications for requirements		
1510	Break		
Session V: Evolution of the network		Chair	N. Smith
1540	Summary from solicited inputs		P. Chapman
1610	Discussion of draft background report (including detail)		
1700	Work Plan for Final Report		N. Smith
1730	Adjourn		
1745	Vans depart for the Silver Cloud Inn		

Wednesday, September 12

0745	Vans depart Silver Cloud Inn		
0800	Coffee		
Session V (continued): Evolution of the network		Chair	N. Smith
0830	Consideration of logistical and resource issues		
0900	Science goals for the tropical moored buoy network • Outline of conclusions and input to final Report		
1000	Break		
1030	Metrics for ongoing evaluation and evolution • Outline of conclusions and input to final Report		
11.45	Lunch on your own		

Session VI: Workshop Results Chair N. Smith

1245 Recommended network strategy for the near term

1345 Workshop report structure, content, review P. Chapman

1430 Conclusions and Recommendations

- Adjourn
- Shuttles depart for SEATAC airport, vans depart for Silver Cloud Inn

1600 Scientific Organizing Committee wrap up

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APPENDIX III: INVITATION LETTERS

From:
Neville Smith
Chair, Ocean Observations Panel for Climate
PO Box 1289K
150 Lonsdale Street
Melbourne, Vic 3001
Australia

Tuesday, 5 June, 2001

Dear

We seek your assistance in conducting a review of the global tropical moored buoy network.

Tropical mooring arrays are an integral component of the sustained ocean observing system. The first International Conference on the Ocean Observing System for Climate (OceanObs '99) confirmed the importance of the equatorial Pacific mooring array (TAO and TRITON), principally for ENSO prediction. A pilot array has been deployed in the tropical Atlantic (PIRATA) to monitor tropical Atlantic variability, and an initial design has been drafted for an Indian Ocean array. This tropical moored buoy network supports a range of scientific initiatives, including those of CLIVAR, and provides data for various operational applications within the framework of GOOS.

At the 5th meeting of the Ocean Observations Panel for Climate (OOPC, June 2000), the Panel concluded that an assessment of the effectiveness and efficiency of the tropical mooring network was required. Maintenance of the existing arrays was becoming more difficult because of logistical issues (e.g., vandalism, servicing) and the efficiency of the approach was continually being examined. Changing operational and research requirements were also impacting decisions on the future evolution of the network. The Panel concluded that a long-term vision for the network was needed and that a mechanism for quantitative evaluation of performance and effectiveness was required. This view was supported by the Tropical Moored Buoy Array Implementation Panel (TIP, November 2000) and the CLIVAR Ocean Observations Panel (CLIVAR OOP, March 2001).

These three international science and implementation panels–the OOPC, the TIP, and the CLIVAR OOP–have concluded to jointly conduct a review specifically to develop this long-term vision and evaluation mechanism for the tropical moored buoy network. Similar reviews have been conducted for the sea level network (June 1997) and the upper ocean thermal (ship-of-opportunity) network (August 1999); these reviews have proven very effective in guiding the evolution of these contributions to the global ocean observing system.

The Terms of Reference for the moored buoy network review are attached. The review will be based on existing documents (e.g., the OceanObs papers), solicited inputs and an International Workshop (to be held in Seattle, 10-12 September 2001). The review will document the rationale for the network, evaluate recent performance in terms of meeting programmatic objectives, assess the complementarity with other networks of the climate observing system, recommend a set of metrics for on-going evaluation, and recommend a strategy for evolution of the network.

The review process is being guided by an *ad hoc* Scientific Organising Committee chaired by N Smith (other members are Mike McPhaden, Gilles Reverdin, Peter Hacker, and Piers Chapman).

Piers Chapman has agreed to work as a special consultant for this review. He will consolidate the written submissions, compile other background material, and will assist in the drafting and the production of the review report.

The expected outcome of the review and Workshop will be an agreed strategy for the future evolution of the tropical mooring array. The outputs will include documentation of the past and current performance of the network and a set of recommendations for implementation of the strategy.

Your assistance in copnducting this review would be greatly appreciated. We are requesting a written submission against the attached terms of reference and within the general guidelines provided above. While we would appreciate your views against all terms of reference and a broad assessment of the value of the tropical moored buoy network (for your own work and that of your organisation), we are particularly interested in (a) ongoing use in operational systems (climate, ocean and weather) and (b) as input to research efforts.

Submissions should be sent to:

P. Chapman
chapman@ocean.tamu.edu
Dept Oceanography
3146 TAMU
Texas A&M University
College Station TX 77843-3146
USA

Submissions by email are preferable, with text attached in MS Word format and graphics attached as ps or pdf files if possible. Please provide your input by July 15, 2001. If you wish further information do not hesitate to contact myself (N.Smith@BoM.gov.au) or Dr Chapman.

Yours sincerely,

Neville Smith

Chair, Scientific Organizing Committee

From:
Mike Johnson
NOAA/OGP
1100 Wayne Ave., Suite 1210
Silver Spring, MD 20910

Tuesday 16 May, 2001

Dear climate scientists, data users and data providers:

You are invited to participate in an International Workshop to review the requirements for the global network of tropical moored buoys, and to develop a strategy for the future evolution of the network in the context of the composite global climate observing system.

Tropical moored buoy arrays are an integral component of the sustained ocean observing system for climate. The first International Conference on the Ocean Observing System for Climate (OceanObs '99) confirmed the importance of the equatorial Pacific mooring array (TAO and TRITON), principally for ENSO prediction. A pilot array has been deployed in the tropical Atlantic (PIRATA) to monitor tropical Atlantic variability and an initial design has been drafted for an Indian Ocean array. This tropical mooring network supports a range of scientific initiatives, including those of CLIVAR, and provides data for various operational applications within the framework of GOOS.

At the 5th meeting of the Ocean Observations Panel for Climate (OOPC, June 2000), the Panel concluded that an assessment of the effectiveness and efficiency of the tropical mooring network was required. Maintenance of the existing arrays was becoming more difficult because of logistical issues (e.g., vandalism, servicing) and the efficiency of the approach was continually being examined. Changing operational and research requirements were also impacting decisions on the future evolution of the network. The Panel concluded that a long-term vision for the network was needed and that a mechanism for quantitative evaluation of performance and effectiveness was required. This view was supported by the Tropical Moored Buoy Array Implementation Panel (TIP, November 2000) and the CLIVAR Ocean Observations Panel (COOP, March 2001).

Consequently, these three international science and implementation panels–the OOPC, the TIP, and the COOP–have concluded to jointly conduct a review specifically to develop this long-term vision and evaluation mechanism for the tropical moored buoy network. Similar reviews have been conducted for the sea level network (June 1997) and the upper ocean thermal (ship-of-opportunity) network (August 1999) and these reviews have proven very effective in guiding the evolution of these contributions to the global ocean observing system.
The Terms of Reference for the review are attached below. The Workshop will review the rationale for the network, evaluate recent performance in terms of meeting programmatic objectives, assess the complementarity with other networks of the climate observing system, recommend a set of metrics for on-going evaluation, and recommend a strategy for evolution of the network.

The review will be based on existing documents (e.g., the OceanObs papers), and solicited inputs from users and providers of climate data. Additionally, it is anticipated that much of the background for the Atlantic contribution to the global network will be presented at the CLIVAR Tropical Atlantic meeting in Paris, the week of 3-7 September 2001.

The review process will be guided by an *ad hoc* Scientific Organising Committee chaired by N Smith. Piers Chapman has agreed to work as a special consultant for this review; he will consolidate the written submissions, compile applicable inputs from the OceanObs papers, the CLIVAR Atlantic meeting, and other background materials, and he will assist in the drafting and the production of the Workshop Report.

The Workshop will be held at the NOAA Pacific Marine Environmental Laboratory (PMEL) in Seattle, USA, 10-12 September 2001. Additional information regarding workshop details and logistics will be forthcoming. A limited amount of travel support is available. Please confirm your participation in the Workshop by 15 June 2001. With your reply, please also indicate if you will require assistance with travel costs. Mike Johnson is the point of contact (m.johnson@noaa.gov).

Regards,

Mike Johnson

APPENDIX IV: ACRONYMS

AATSR	Advanced Along-Track Scanning Radiometer
ADCP	Acoustic Doppler Current Profiler
ADEOS	Advanced Earth Observing System satellite (Japan)
ATLAS	Autonomous Temperature Line Acquisition System
AVHRR	Advanced Very-High Resolution Radiometer
BATS	Bermuda Atlantic Time Series
CLIVAR	Climate Variability and Predictability programme
COARE	Coupled Ocean-Atmosphere Response Experiment
COLA	Coupled Ocean-Land-Atmosphere [Model]
COSTA	Climate Observing System for the Tropical Atlantic
DBCP	Data Buoy Cooperation Panel
DMSP	Defense Meteorological Satellite Program (U.S.)
ECCO	Estimation of the Circulation and Climate of the Ocean [model]
ECMWF	European Centre for Medium-Range Weather Forecasting
EEZ	Exclusive Economic Zone
ENSO	El Niño-Southern Oscillation
EPIC	Eastern Pacific Investigation of Climate [Processes in the Coupled Ocean-Atmosphere System]
EOS	Earth Observing System
ERS	ESA Remote Sensing satellite
FNMOC	Fleet Numerical Meteorology and Oceanography Center (U.S.)
GCOS	Global Climate Observing System
GEOSAT	(U.S. Navy) Geodetic Satellite
GEWEX	Global Energy and Water Cycle Experiment
GFDL	Geophysical Fluid Dynamics Laboratory (Princeton)
GODAE	Global Ocean Data Assimilation Experiment
GOOS	Global Ocean Observing System
GTS	Global Telecommunications System
HOTS	Hawaii Ocean Time Series
IMET	Improved Meteorological measurement package
IOC	Intergovernmental Oceanographic Commission
IOD	Indian Ocean Dipole
IPRC	International Panel for Research on Climate
IRD	Institut de la Recherche et Developpement (France)
ISO	Inter-Seasonal Oscillation
ITCZ	Inter-Topical Convergence Zone
ITF	Indonesian Throughflow
JAMSTEC	Japan Marine Science and Technology Centre
JCOMM	Joint Commission on Oceanography and Marine Meteorology
JMA	Japan Meteorological Agency
MJO	Madden-Julien Oscillation

NASA	National Aeronautics and Space Administration (U.S.)
NCDC	National Climate Data Center (U.S.)
NCEP	National Center for Environmental prediction (U.S.)
NOAA	National Oceanic and Atmospheric Administration (U.S.)
NOR	Navire Oceanographique Rapide
NRC	National Research Council (U.S.)
NSCAT	NASA Scatterometer
NWP	Numerical Weather Prediction
OOPC	Ocean Observations Panel for Climate
OOSDP	Ocean Observing System Development Panel
ORSTOM	Office de la Recherche Scientifique et Technique Outre Mer (France)
PALACE	Profiling Autonomous Lagrangian Circulation Explorer
PBECS	Pacific Basin Extended Climate Study
PIRATA	Pilot Research Moored Array in the Tropical Atlantic
PMEL	Pacific Marine Environmental Laboratory (U.S.)
POGO	Partnership for Observation of the Global Oceans
SMOS	Salinity Measuring Ocean Satellite
SOCIO	Sustained Observations for Climate of the Indian Ocean
SOOP	Ship-of-Opportunity Panel
SSM/I	Special Sensor for Microwave/Imager
SSS	Sea Surface Salinity
SST	Sea Surface Temperature
TAO	Tropical Atmosphere Ocean
TBO	Tropical Biennial Oscillation
TIP	Tropical Moored Buoy Implementation Panel
TOGA	Tropical Ocean-Global Atmosphere
TOPEX/POSEIDON	Ocean Topography Experiment (NASA/CNES satellite program)
TRITON	Triangle trans-Ocean Buoy Network
T/S	Temperature/Salinity
UKMO	Meteorological Office (U.K.)
VOS	Volunteer Observing Ship
WCRP	World Climate Research Programme
WMO	World Meteorological Organization
WOCE	World ocean Circulation Experiment
WWW	World Weather Watch
XBT	Expendable Bathythermograph
XCTD	Expendable Conductivity, Temperature, Depth instrument