On The Design and Implementation of Argo

A Global Array of Profiling Floats

The Argo Science Team[1]

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Preface

This document describes some initial ideas for the design and implementation of *Argo*, a global array of autonomous profiling floats. The original concept grew out of two independent, but connected, initiatives, "*A Proposal for Global Ocean Observations for Climate: the Array for Real-time Geostrophic Oceanography"* (ARGO), by Dean Roemmich, and "*A program for Global Ocean SAlinity MonitORing*" (GOSAMOR), by Ray Schmitt. Early in 1998 the International Steering Team for GODAE (the Global Ocean Data Assimilation Experiment) endorsed the broad concept of such an array and undertook to develop a plan. In the 2nd quarter of 1998 the Upper Ocean Panel of CLIVAR also considered these proposals and unanimously agreed that such an initiative must be given high priority in the CLIVAR Implementation plans.

In July of 1998 a Workshop was held in Tokyo to discuss the prospects for *Argo* and an initial outline for a plan was drawn up. At that Workshop, which was jointly convened by GODAE and the CLIVAR UOP, an *Argo* Science Team was appointed with the charge to produce an initial design and implementation plan. The present document is the response to that charge.

An initial draft of this document was widely circulated through the oceanographic and climate community for review. This review drew many comments and suggestions and raised a number of significant issues. Because of time constraints, and the need to have a document available for the CLIVAR Conference in December of 1998, we, as Chairs of the convening bodies, decided that a detailed revision was not wise, and probably not possible, on this time frame. Many of the issues require detailed scientific study and need some time for fuller consideration. As an interim measure, we have attended to a few of the more pressing issues, and prepared a consolidated list of issues and items for consideration by the Science Team at a later time.

This document then represents an initial set of ideas for the design and implementation of *Argo*, and presents the scientific rationale for proceeding with *Argo*. We think you will find the case for *Argo* a strong one, and that the initiative, though ambitious, both doable and worth doing.

We thank the *Argo* Science Team, and other contributors, for this paper, and look forward to the early development of a more detailed design and complete implementation plan.

Neville Smith
Chair of the International GODAE Steering Team

and

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Executive Summary

A plan for a new network of autonomous profiling floats is described with the potential to greatly enhance the present level of upper ocean temperature and salinity measurement. Such enhancements are urgently needed to sustain improved understanding of climate variability and ocean variability over a range of space and time scales and to underpin a range of operational oceanographic applications. This project has been named *Argo*, in part because of the expected complementarity with the *Jason* altimetry mission.

The primary practical goal of *Argo* will be to provide an enhanced real-time capability for measurement of temperature and salinity through the upper 2000 m of the ocean and contribute to a global description of the seasonal cycle and interannual variability of the upper ocean thermohaline circulation. The profiling float is expected to gather up to 100 profiles of temperature and salinity over a lifetime of 3-4 years. Improvements in the technology have also made it a very cost-effective option.

The design emphasizes the need to integrate *Argo* within the overall framework of the global ocean observing system. *Argo* will strengthen the complementary nature of the direct and remote observing systems, filling the large gaps that presently exist in the global sampling network, and provide essential information for ocean state estimation. The network, when integrated with other elements of the climate observing system, will greatly enhance studies of climate variability on interannual time scales and deliver information for initialization of climate predictions and studies of climate predictability.

The combination of *Argo* and altimetry will enable a new generation of applications. Global maps of sea level, on time scales of weeks to several years, will be interpreted with full knowledge of the upper ocean stratification. The vertical dependence of the oceanic response to surface forcing will be in view. Global ocean and climate models will be initialized, tested and constrained with a level of information hitherto not available. An adequate sampling network will be in place as a foundation for future studies of climate variability and predictability.

The initial design of the network is based on experience gained with observing systems in other climate experiments, on newly gained knowledge of variability from the Topex/Poseidon altimeter, and on estimates of the requirements for climate and high-resolution ocean models. Such sampling studies as do exist suggest that a broad-scale array with O(200-300) km resolution is capable of resolving many of the important global climate signals. This experience and knowledge is limited so the design must be evolved as further experience and knowledge are gained. The drift estimates from such an array would in addition provide useful estimates of deep pressure fields (reference level).

The oceanographic community is entering a new era where ocean models and data assimilation and ocean state estimation will be the preferred methods for utilizing data. Applications are numerous and varied, including initialization of ENSO forecast models, initialization of short-range ocean forecasts, routine production of high-quality global ocean analyses, and studies of predictability on interannual and decadal time scales. The *Argo* array will provide unprecedented information, particularly with respect to salinity, in such applications. The information will be exploited to improve, or develop for the first time, estimates of process and error covariances, a pre-requisite for ocean estimation. The level of precision and detail that *Argo* will enable is not possible with present networks.

A range of modeling studies to support and develop the *Argo* design is recommended. Models will be seeded with synthetic particles (floats) to test the appropriateness of proposed sampling rates, the optimum profile characteristics (including park depth), and possible effects (positive and negative) of dispersion and congregation of floats. The studies will typically be carried out with eddy-resolving models.

This document identifies the many significant technical challenges that must be addressed on the path to implementation, including issues associated with data management, telemetry and data assembly. The document concludes with a discussion of these issues and an outline of intended action items for the *Argo* Science Team.

I. Autonomous Profiling Floats – The New Capability for Global Sampling of Ocean Climate Variability

The 1998 Year of the Oceans has focussed international attention on the ocean and on related societal problems such as the ocean's role in climate maintenance and change, ocean prediction, and environmental sustainability in the coastal zone. For each of these, there is a fundamental dependence on ocean data. Our inability to observe the ocean at resolutions that are appropriate and useful has effectively limited progress until now, especially with respect to climate. However, thanks to recent advances, the technologies now exist for the first time to collect datasets that match the breadth, depth and scales of climate signals in the World Ocean.

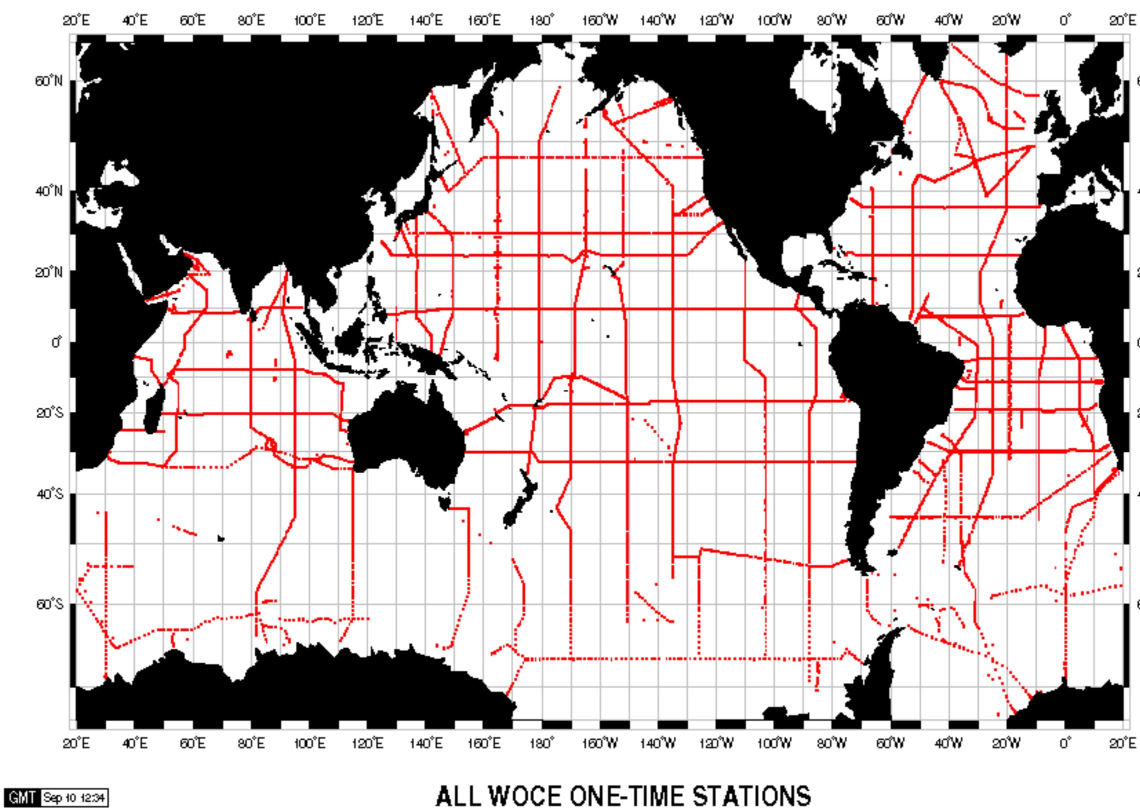

Figure 1. Map of station locations in the WOCE Hydrographic Project global one-time survey. Most stations were occupied during 1991-1997.

Limitations on the quantity and quality of oceanographic data have been closely tied in the past to the presence of ships used for data collection. The collection of highest quality hydrographic data (temperature and salinity profiles) is technically and logistically demanding. It requires dedicated research vessels, sophisticated instrumentation, and skilled technical teams. Only in the present decade has the World Ocean Circulation Experiment (WOCE) managed to carry out a global hydrographic survey. WOCE required seven years and the combined resources of many nations to obtain a single sparse realization of temperature, salinity, velocity (T,S,v) and geochemical tracers. The impressive WOCE one-time survey (Fig. 1) includes about 9,000 top-to-bottom profiles collected in all oceans during 1991-97.

Measurement of upper-ocean temperature variability on large spatial scales became practical in the 1960's with the advent of the expendable bathythermograph (XBT) and the Ship-of-Opportunity Program. Increased and continuing ocean-scale coverage with XBTs was encouraged by the major climate programs of the past decade, WOCE and the Tropical Ocean Global Atmosphere (TOGA) Experiment. During the 1990's about 40,000 XBT profiles have been collected to 450m or 750 m depth per year. The Tropical (formerly TOGA) Atmosphere Ocean array (TAO), and other moorings, provides in excess of 20,000 additional vertical profiles. Fig. 2 shows a typical thermal profile coverage for a single month. Although valuable for its spatial and temporal coverage, the XBT dataset has serious deficiencies. It includes temperature only - of relatively poor quality and with no salinity or velocity - and sampling is restricted to shipping routes. Spatial distribution is badly skewed in space and time, with gaps of several thousand kilometers being common even in annual inventories, and almost no sampling south of 30^{o}S (Fig. 2). It is widely recognized (e.g. OOPC, 1995, CLIVAR Implementation Plan, 1998) that substantial improvements are essential to making progress in understanding seasonal to decadal signals in climate.

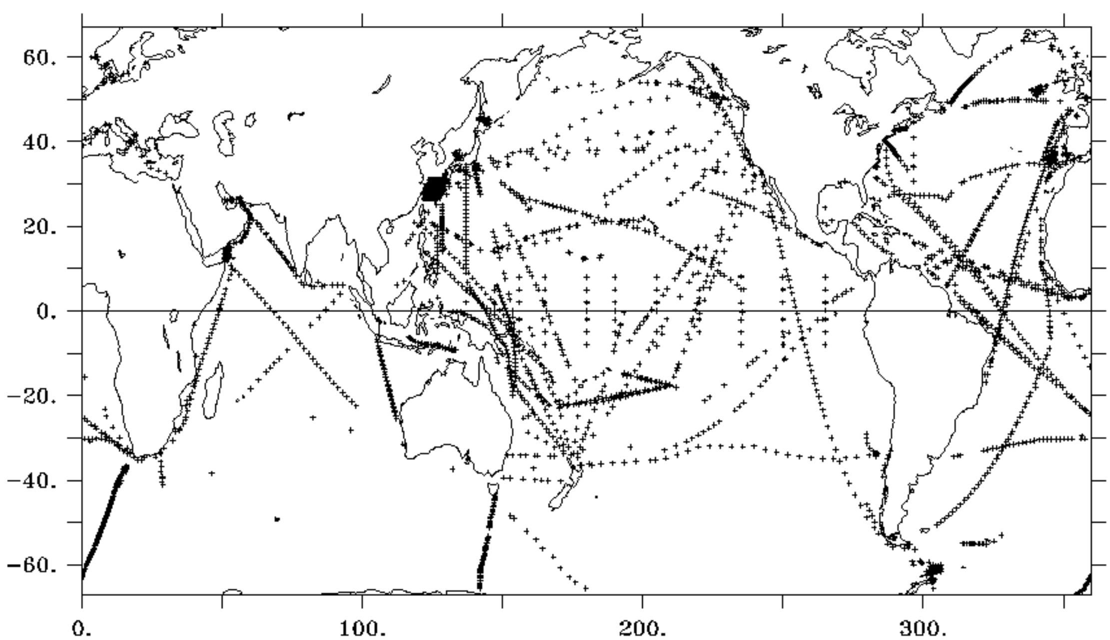

Figure 2. Map of subsurface ocean temperature profile locations for January 1995, including real-time and delayed mode profiles. The regular north-south points in the tropical Pacific are from TAO.

The development of autonomous profiling floats (Fig. 3) provides a key to help free the large-scale oceanographic data collection process from the dependency on ships. Spatial and temporal sampling limitations inherent in global hydrographic and XBT surveys have been overcome through this development. Neutrally buoyant satellite-tracked floats were developed in WOCE and deployed in all oceans to measure absolute velocity. In later years of WOCE, the Atlantic deployments included temperature and salinity profiling to 1200 m depth. The present generation of floats is capable of approximately 100 cycles, each including a T/S profile to about 1500 m depth and a drift velocity measurement at any level between the sea surface and the profile base. Accuracy of approximately .01^{o}C in temperature and .01 psu in salinity is attainable – the latter requiring a stable water mass at depth for reference.

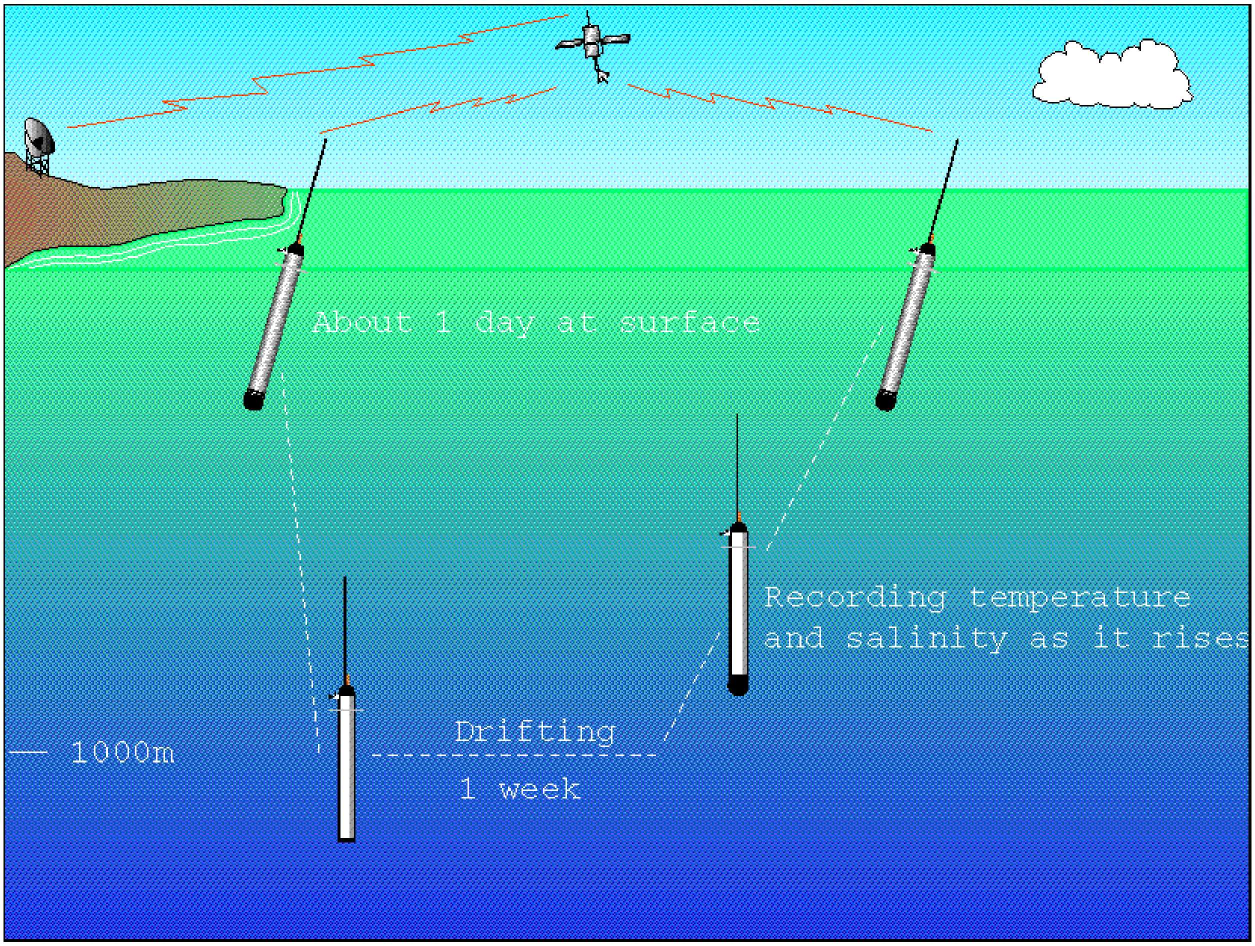

Figure 3. Schematic diagram of a single cycle in the mission of a profiling float. Float lifetime is expected to be about 80-100 cycles.

While further development is needed to enable deep ocean measurements and for more stable salinity, the present generation of floats and sensors is adequate for sampling the upper ocean and thermocline waters. Floats can be deployed anywhere in the global ocean, except for permanently ice-covered regions, to operate autonomously, with real-time satellite telemetry of the physical data and the drift displacement at depth. The best available advice at this time is that *Argo* floats could operate for around 3-4 years, performing cycles of 2000 m every 14 days, and thus delivering around 80-100 profiles of temperature and salinity per deployment. A more recent development, a profiling float equipped with wings for dynamic positioning during ascent and descent, offers further potential. This “gliding” float will provide a similar number of T/S profiles at a fixed location or along a programmed track.

This document describes the objectives and benefits of a global array of profiling floats within the broader context of a climate observing system in the ocean. Profiling floats cannot satisfy all the requirements of a comprehensive ocean observing system. However, the new technology is a major step forward. It enables the first regular sampling of the global ocean on broad spatial scales and makes a comprehensive observing system possible. For this reason, the implementation of a float array should help to focus the planning and justification of other important elements of the measurement system. Part II of this document outlines the scientific case for deployment of a global array of floats. The combination of these *in situ* technologies with satellite observations of the sea surface adds enormous capability to the present observing system. Part III spells out the specific requirements and design criteria that provide the best present guess of the array's configuration and of what it will accomplish. Finally, the implementation of the global array is discussed in the closing section.

II. The Scientific Objectives of the Global Float Array

A. The GODAE/CLIVAR context

Scientifically, the global array of profiling floats sits at the intersection of two major initiatives, Climate Variability and Predictability (CLIVAR) and the Global Ocean Data Assimilation Experiment (GODAE). Within the climate research context set by CLIVAR and the operational estimation objectives of GODAE, the primary practical goal of *Argo* is to

- ***Provide an enhanced real-time capability for measurement of temperature and salinity through the upper 2000 m of the ocean and contribute to a global description of the seasonal cycle and interannual variability of the upper ocean thermohaline circulation.***

The name *Argo* was chosen because of the projected strong complementarity between this float project and the *Jason-1* altimetric mission. *Jason* and *Argo* provide a powerful synergy: regular global sea surface heights together with the subsurface measurements provide information that is critical for the determination of the ocean circulation and its physical state.

Argo aims to realize a truly global real-time sampling of upper ocean temperature and to provide the first coherent images of variability in the subsurface salinity field. It will not only provide a valuable complement to satellite data, but will also satisfy a broad range of applications in research and operational monitoring and prediction.

GODAE is an experiment in global ocean state estimation, with applications ranging from the provision of boundary conditions for coastal prediction systems to initialization of climate models. Its overall aim is to demonstrate the viability, feasibility and practicality of operational oceanography. The need for subsurface ocean data in GODAE is two-fold. First, present assimilating models are not yet capable of realism if they are constrained only by surface forcing and surface height (see III.E. below). Subsurface data are needed to constrain the vertical response. Second, in order to guide the improvement of these models, measurements are needed for comparison and testing. Thus, for example, measurements of heat and freshwater storage are a fundamental requirement to test a climate model. Subsurface data must satisfy these needs until their redundancy is demonstrated.

At its first meeting, the GODAE Scientific Steering Team concluded that a significant enhancement of the global *in situ* ocean observing network is necessary for the successful execution of the experiment in 2003-2005. A major float deployment was recommended to meet this requirement. The float network is needed to enable global coverage with both salinity and termperature, to provide more frequent, real-time samples of the ocean and to complement other components of the GODAE system. The GODAE strategy emphasizes the complementary role of the direct and remote observing networks and the role of models and data assimilation in integrating incoming information and producing useful and practical outputs.

The focus of CLIVAR is improved understanding of climate variability and predictability and the development of models useful for prediction. The time scales range from the intraseasonal scales of the monsoon systems, through interannual scales of phenomena like El Nino, to decadal variations such as those seen in the North Atlantic and North Pacific Oceans, to even longer trends. For an adequate description of variability in the coupled climate system, it is necessary to observe fluctuations in the storage, transport and air-sea exchange of heat, freshwater and momentum on sub-gyre to global scales.

At its 1998 meeting, the CLIVAR Upper Ocean Panel recommended the implementation of a global network of profiling floats. A global sustained network of temperature and salinity observations is critical for most of CLIVAR's Principal Research Areas (PRAs). The network should be integrated with other elements of the climate observing system,

- *to detect climate variability on seasonal to decadal time-scales. The targeted variability includes changes in the large-scale distribution of temperature and salinity and in the transport of these properties by large-scale ocean circulation.*
- *to deliver information needed for calibration of satellite measurements, and*
- *to provide data for initialization and constraint of climate models.*

The most serious defects in present networks are the lack of global span in thermal data and the lack of any systematic subsurface salinity data. These are major weaknesses, in effect limiting scientific progress in climate studies.

Argo is also needed to accelerate the development of ocean models and data assimilation, providing key data for testing and constraining ocean and coupled ocean-atmosphere climate models. Lack of adequate subsurface temperature and salinity data is a severe barrier to developing useful and reliable estimates of the ocean physical state, even in the presence of satellite data from altimetry, radiometers (sea surface temperature) and scatterometry (surface wind stress).

GODAE and CLIVAR provide a strong scientific rationale for immediate action. Without the enhancements proposed herein GODAE and CLIVAR will be limited in scope. Both argue for an integrated approach whereby the recommended enhancements are seen as complementary and value-adding for the operational sustained global ocean observing system. Without such an enhancement, the existing and planned investment in remote sensing, other forms of direct measurement, and modeling will not realize their potential. The proposal is consistent with the recommendations of the Ocean Observing System Development Panel and its successor, the Ocean Observations Panel for Climate with respect to the establishment of long-term global ocean and climate observing systems.

B. Combining profiling floats and altimetry for diagnosis of the climate system

As noted above, one practical outcome from the global float array is that it will complement and amplify the climate-relevant information of the satellite network, especially the Jason-1 altimeter and its successors. In order to expand on this objective, an explanation of the relationship of altimetric data to profiling float data is given.

Fluctuations in sea surface height can be decomposed into the variability of pressure at a fixed reference level plus the variability due to temperature and salinity structure of the overlying water column. Thus, anomalies in altimetric height may be written as

$$h'_{alt} = \frac{\alpha \; p'_{ref}}{g} + \frac{1}{g}\int_{p_{ref}}^{0} \alpha' \, dp + Errors \qquad (1)$$

where h is height, α is specific volume (a function of temperature, salinity and pressure), p is pressure, g is gravitational acceleration, and primes are used to denote anomalies. The second term on the right (known as steric height or dynamic height) is calculated directly from the float profile data by substituting temperature and salinity into the equation of state for seawater. The first term on the right is obtained indirectly from the float's drift velocity (e.g. Davis, 1998) via the geostrophic relationship,

$$u = -\frac{1}{\rho f}\frac{\partial p}{\partial y}, \quad v = \frac{1}{\rho f}\frac{\partial p}{\partial x} \qquad (2)$$

where f is Coriolis acceleration, u and v are zonal and meridional velocity, and ρ is density ($1/\alpha$). Hence, the role of profiling float data is to diagnose both the steric and reference pressure contributions to sea level. The float array can never match the high along-track spatial resolution of altimetric data, but it can reveal the underlying structure of the sea level signal. That structure is critical to improved understanding of the climate system because it defines the oceanic response to forcing by wind stress, heat and freshwater exchanges. The ocean is the primary reservoir and an important conduit for heat and freshwater in the coupled air-sea-land system. The improvement of diagnostic and predictive models of the climate system requires substantially better understanding of internal oceanic variability.

Over most of the ocean, the steric contribution to sea level is dominant over deep reference pressure variability. The similarity of sea level gauges and steric sea level on seasonal and longer time-scales is well documented (e.g. Patullo et al, 1955, Schroeder and Stommel, 1969). A recent comparison of TOPEX data with quarterly XBT transects of the North Pacific Ocean (Gilson et al, 1998) revealed high coherence between altimetric height and steric height on a broad range of spatial scales, with coherence amplitude 0.9 for wavelengths longer than 500 km (Fig. 4). In regions where the steric contribution dominates, altimetric height is highly correlated with subsurface variability and the correlation can be exploited to estimate subsurface temperature or density fields from altimetric data (a technique known as the “synthetic XBT”). This technique, where appropriate, is a powerful means of combining the high spatial resolution of altimetric data with statistical information from sparser profiles. However, it should be borne in mind that the requirements for adequate climatologies and statistics – appropriate to the time-scales of interest - place substantial and continuing demands on the *in situ* database.

Although reference pressure variability is a small contributor to sea surface height in some regions, it becomes increasingly significant at higher latitude. The stratification is diminished there and the oceanic response to wind-forcing becomes more depth-independent. This results in decreased correlation of steric height and sea level. In such cases, the need for subsurface data seems especially obvious because accurate statistically based estimates of subsurface fields from altimetric height are not possible. However, even in the tropics, where the steric contribution dominates the variance, the reference pressure variability may be significant on seasonal and longer time scales (Gilson et al, 1998). In any case, it is important to know the depth-independent response of the ocean for dynamical understanding. Initially, the subsurface array by itself should be capable of observing the climate signals of interest, without depending on statistical linkage to the more highly resolved altimeter. Once it can be demonstrated that the depth independent contribution to sea level is known, then the subsurface array can be reduced, consistent with optimizing the statistical link to altimetric data.

C. Initialization and constraint of operational models

Operational ocean and coupled ocean-atmosphere models are run in a number of countries and for a variety of purposes, including monitoring and predicting El Nino – Southern Oscillation (ENSO, e.g. NCEP, Ji and Leetmaa, 1997; ECMWF, Stockdale et al, 1998; BMRC, Kleeman et al, 1995) and operational ocean analyses (FNMOC, Clancy et al, 1990; NCEP, Ji and Leetmaa, 1997; BMRC, Smith, 1995; UKMO, Foreman, 1992). For seasonal forecasting, the dependence on subsurface data has been demonstrated several times (see the above references). One of the significant factors distinguishing models that were able to capture and forecast aspects of the 1997 El Nino was the ability to ingest subsurface data. The majority of ocean analysis systems are striving for global estimates of subsurface ocean temperature. However all are limited by the available data. The advantages of large space and time scales are quickly lost outside the tropics and so the need for in situ data is much stronger, even when satellite data are available. This lack of data also inhibits regional models (e.g., coastal forecasting) because of the difficulty in estimating the ocean state at the external boundaries.

While it may be argued that all of the above assimilation systems are inefficient users of ocean information, a situation that is compounded by model problems and lack of good surface data, all clearly need improved input data, both in terms of global coverage and in terms of depth (see OOSDP 1995 for a discussion).

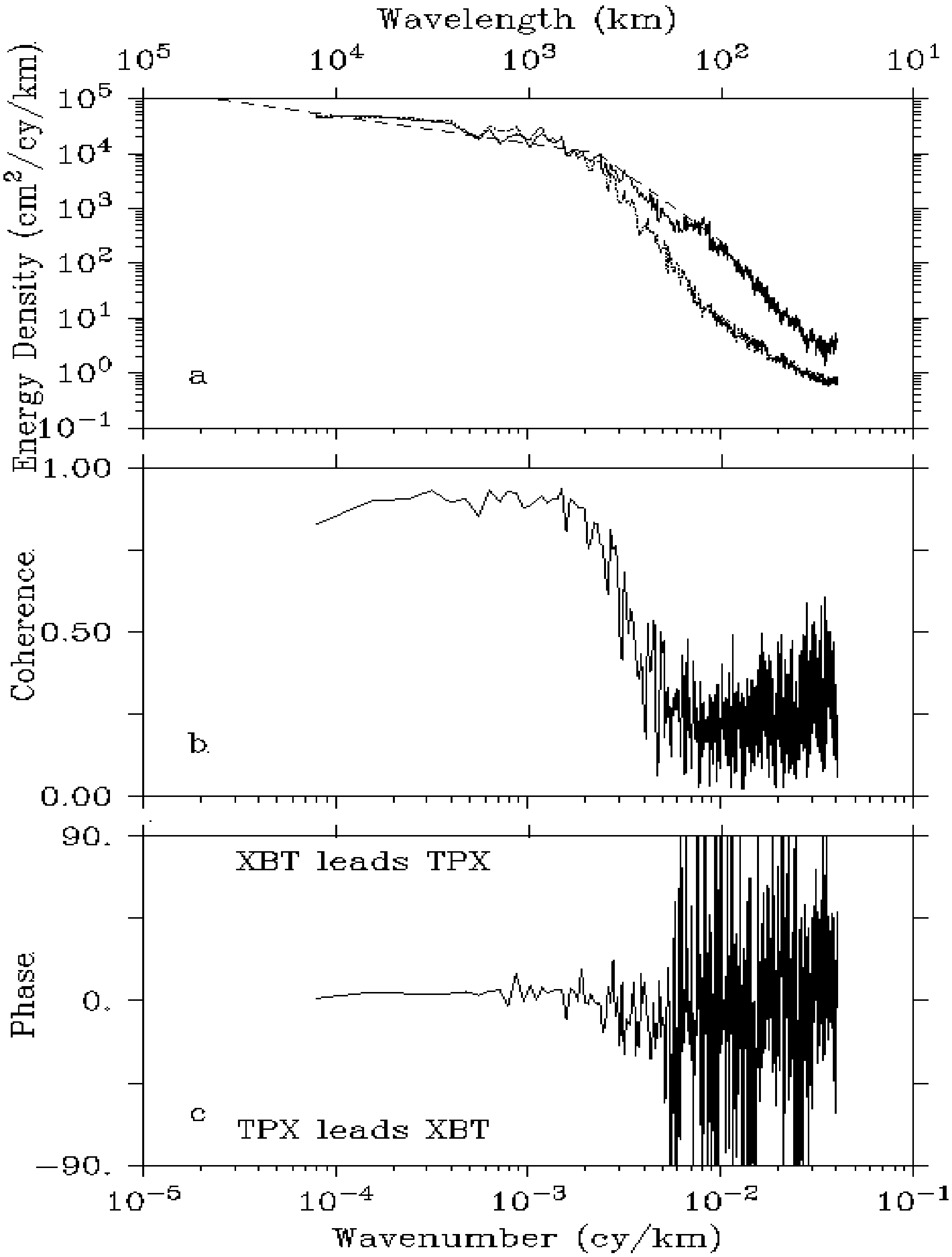

Figure 4. Upper panel - Spectra of altimetric sea level(dotted) and steric height (solid) from 20 high resolution XBT/XCTD transects between San Francisco and Taiwan (from Gilson et al., 1998). Middle and lower panel - Coherence amplitude and phase of altimetric sea level and steric height.

The specific need for salinity data to improve the NOAA simulations has been shown by Acero-Scherzer et al. (1997). They show that the lack of salinity profiles results in erroneous representations of the surface pressure field and thus geostrophic currents. Additionally, models run at ECMWF that assimilate only temperature and altimetry data produce unrealistic excursions of isopycnal surfaces because of poor salinity representations (David Anderson, personal communication, 1998). The salinity data provided by ARGO will improve the accuracy of ocean simulations in present and future operational models.

III. The Design of Argo

The design of Argo should draw on the entire present knowledge of the requirements for global broad-scale sampling by using results from subsurface measurements, satellite observations and modeling studies. It is not yet possible to design an optimal global array because the present observing system is too far removed from optimal. For example, the Southern Ocean lacks sufficient data to define even the annual cycle of sub-surface temperature. For salinity, the situation is far worse than for temperature. Thus, the design process must be an iterative one, based on numerical studies as well as data, with the accumulated information at any given time used to assess the ongoing needs. A number of datasets and approaches can contribute usefully to the initial design of Argo. By considering each of these, it is possible to frame the design problem in several different ways. If disparate approaches give consistent results this will provide some reassurance in the face of the shortcomings of each estimate individually. The following sources of information provide critical guidance for the design:

• ***The Ship-of-Opportunity XBT and moorings thermal network.*** Argo will evolve from the present broad-scale XBT network and (mainly) tropical upper ocean thermal data from moorings like TAO (Fig. 2), with immediate gains in spatial coverage and extent, depth and accuracy, plus the addition of salinity and reference velocity. Successful evolution from the present network requires appropriate consideration of the design and attributes of this network, a principal source of information for *Argo* (Section A).

• ***TOPEX/POSEIDON altimetric data.*** The integration of data from the float program with altimetric data is a key theme of the present plan. The design should therefore stress the ability to resolve known climate-relevant signals as seen by the present altimeter (Section B).

• ***WOCE hydrographic and float data.*** *Argo* is an important successor to WOCE. WOCE floats provide the only existing dataset for estimating specific sampling requirements for reference pressure (Section C). The design should be capable of delineating the evolution and global pattern of climate signals such as those seen in the WOCE hydrographic program (Section D).

• ***Requirements for constraint of ocean models.*** Data from an *in situ* observing system is more powerful when integrated with satellite data and models, to improve ocean state estimation, ocean forecasts and prediction and understanding of the coupled climate system. The requirements for constraint and testing of ocean models are a strong consideration in the design of the observing system (Section E).

A. The evolution of Argo from the existing upper ocean thermal network

XBT data now span three decades, providing a large database of temperature profiles in the tropics and middle latitudes. It is the broad-scale XBT network of TOGA and WOCE that is the most direct precursor to Argo, and whose sampling limitations – lack of salinity, skewed distribution, large gaps and insufficient depth – Argo is designed to obviate. The existing data provide crucial information on the space and time scales of upper-ocean temperature variability.

The tropical ocean moorings (TAO and TRITON in the Pacific; PIRATA in the Atlantic), and other time-series data, are also extremely important elements of the ocean sampling network. These arrays are mainly purposed built (e.g., for prediction of ENSO), with focus on temporal sampling, and so have designs which are different in approach and purpose to *Argo*.

A number of statistical analyses have been carried out previously, using data from the broad-scale XBT network to determine the scales of thermal variability and to improve on the sampling characteristics of the network. These include studies by White and Bernstein (1979, North Pacific Ocean), Phillips et al (1990, Indian Ocean), Meyers et al (1991, tropical Pacific Ocean), Sprintall and Meyers (1991, eastern Pacific Ocean), Festa and Molinari (1992, Atlantic Ocean), and White (1995, global from 30^oS to 60^oN). Here a similar approach is taken, using the historical XBT data to estimate decorrelation scales and noise and signal variances. Once these parameters are determined, optimal interpolation techniques are used to construct maps of sampling error for different sampling strategies. An optimal sampling strategy can be developed by weighing requirements for accuracy against cost.

In the tropical Pacific Ocean, using historical XBT data averaged in 2^o by 2^o areas, zonal decorrelation scales of 12^o longitude and meridional decorrelation scales of 4^o latitude were determined. The noise variance was estimated as 0.18^oC^2; zonal and meridional signal variances were 0.20^oC^2. Using these values, error fields were generated for the present real-time NOAA XBT grid in the tropical Pacific (Fig. 5, upper) for a typical two month period. Then, anticipating results discussed below, a second error map was generated from a field of randomly spaced data at an average spacing of 3^o by 3^o (Fig. 5, lower). The potential for improvement over the present network is obvious. It should be remembered that scales and variances are a function of region and depth.

Uncertainties less than 0.5^oC are shaded in Fig. 5 to represent the achievable accuracy for upper layer temperature estimation. This is equivalent to an accuracy in bimonthly heat content changes of 15 W/m^2 for a 50 m thick layer. At that level of accuracy, errors in seasonal changes in heat content are comparable to the errors sought in air-sea heat exchange estimates. It should be noted that the temperature and heat storage errors can be reduced by temporal or spatial averaging or through combination of *in situ* data with altimetric data (see next section). Of the three terms in the oceanic heat balance - storage, air-sea flux, and ocean heat transport - the storage term is potentially the most accurate because it is not subject to large systematic errors. Large areas exist in the Pacific where the desired accuracy is not available from the present XBT network (Fig. 5). The 3^o by 3^o array attains 0.5^oC accuracy over most of the domain.

White (1995) performed a similar optimal interpolation analysis and concluded that, because of the spatial variability in scales and variances, it is best for a spatially uniform array to resolve "minimal scales". In his global analysis covering 30^oS to 60^oN, he estimated these minimal scales to be 5^o in longitude and 2.5^o in latitude. An error analysis was performed using White's scales and representative variances for the present XBT grid and the hypothetical 3^o by 3^o grid. Because of the shorter scales, somewhat larger areas exist where the 0.5^oC criterion is not met. The error estimates produced using “local scales” and “minimal scales” represent the best guess that can presently be made of the capabilities of a global array, and of the attainable accuracy in estimating changes in broad-scale temperature and heat content.

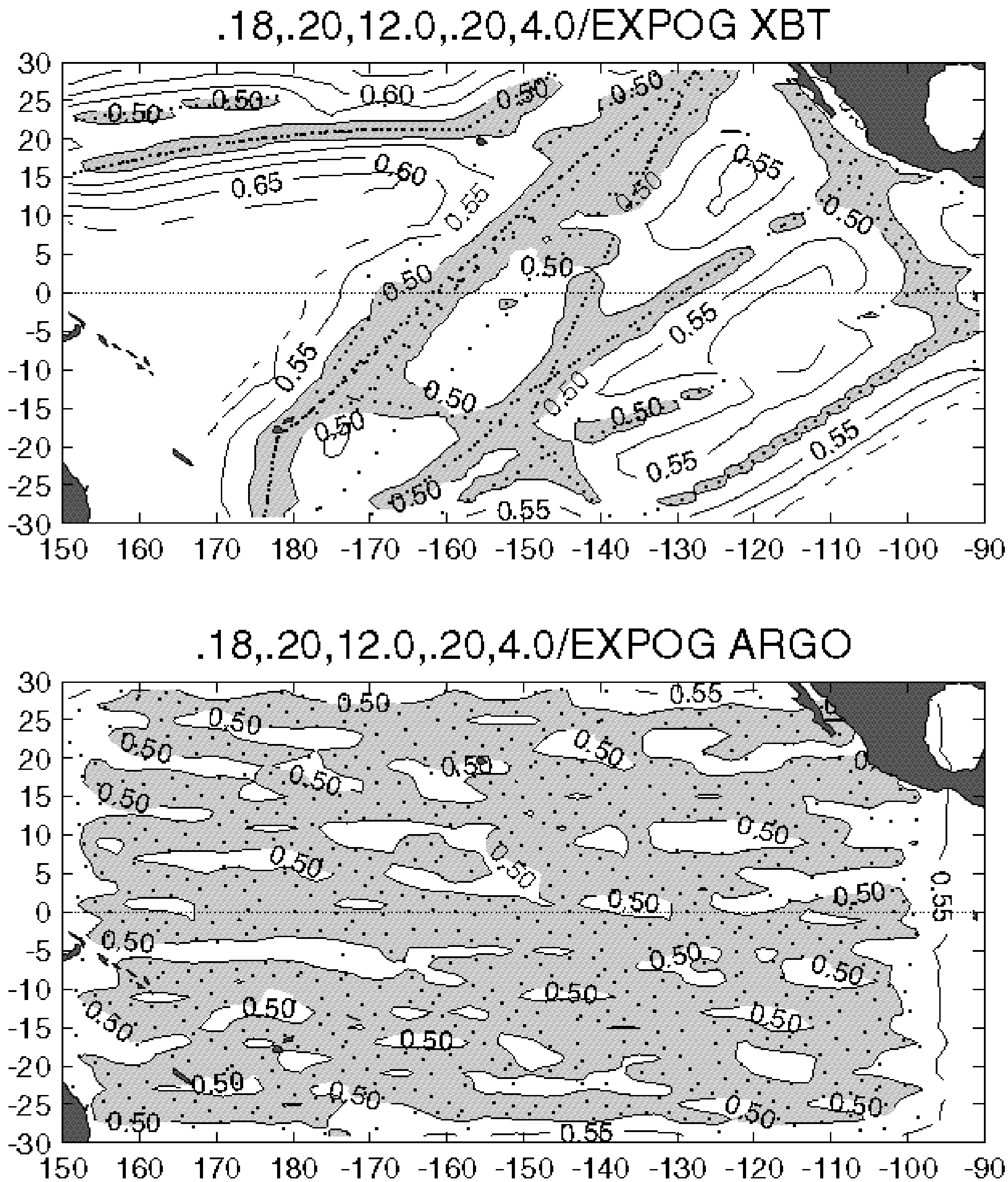

Figure 5. Error maps (^{o}C) for near-surface temperature fields estimated from optimal interpolation based on statistics gathered from well-sampled XBT lines. The upper panel is for the NOAA XBT sampling in the eastern tropical Pacific during January-February 1998. The lower panel is for a random array with average spacing of 3^{o} in latitude and longitude.

B. Using TOPEX/POSEIDON altimetric data in the design of Argo

The TOPEX altimeter measures temporal variability in sea level, and hence in the sum of the steric and reference pressure contributions, as explained above. It provides a valuable proxy for use in designing a network of profiling floats since floats measure those two quantities individually. TOPEX provides global estimates of the resolving power and sampling error for a given array, and sampling error is the primary error in observing climate signals in the ocean. In regions where the steric contribution is dominant, the satellite primarily observes variability in heat and/or freshwater storage. There, the altimeter can provide a direct assessment of Argo sampling errors in the measurement of those quantities. Some caution applies here. Essentially, the altimeter will provide appropriate statistics for Argo sampling if one component dominates sea surface height, or if all components have similar statistics. One would not want to rely solely on the altimeter for design of Argo. Nevertheless, because of its close relationship to Argo, consideration of altimetric data is of great value in the design process. The TOPEX altimeter has now provided six years of regularly repeating global estimates of sea surface height with high accuracy and excellent resolution.

First, the along-track wavenumber spectrum of TOPEX data is considered. Wunsch and Stammer (1995) produced a globally averaged spectrum, finding that 48% of the variance is at wavelengths longer than 1000 km and 70% at wavelengths longer than 500 km. If the climate signal of interest is defined to include all wavelengths longer than 1000 km, then an array with 500 km spacing would provide a 1:1 ratio of signal variance to analysis error variance. Spacing of 250 km would improve this ratio by more than a factor of 3. The unresolved variability – fronts, mesoscale eddies etc. - has a short decorrelation time, typically 10-20 days, compared to the seasonal and longer climate signals of interest. The ratio of signal-to-error can be increased by temporal or multi-track averaging, an issue discussed below.

The globally averaged spectrum does not provide a prescription for sampling everywhere. There is important scale variability with region and latitude, as described by Stammer (1997). He showed a universally valid representation of the zonally-averaged wavenumber spectrum, whose latitudinal dependence on the Rossby radius of deformation illustrates the dominating influence of first vertical mode baroclinic variability. For the Stammer (1997) spectrum (his equation 17), half of the variance is at wavelengths longer than about 700 km at 50^{o} latitude and at wavelengths longer than 1300 km at 10^{o} latitude. This scaling of the spectrum with latitude argues for an increase in sampling density with latitude. In order to halve the spacing in a two-dimensional array, four times as many instruments are required. However, there are several reasons for adopting a less steep latitudinal dependence than called for by the spectral scaling. First, there is little oceanographic data available at high latitude. Almost any sampling will produce a large increment in information and the correct array dimensions for optimal sampling of climate signals are simply not known. The initial array is largely exploratory, to be tuned later. Second, both the statistics and the climate signals are relatively well known in the tropics. The strongest global interannual climate impacts are due to the tropical El Nino/Southern Oscillation (ENSO) signal. An array with good resolution in the tropics will provide important new information on ENSO variability and predictability and is strongly justified. The benefits of a given array, in terms of estimation errors for heat and freshwater anomalies, are best known in the tropics (e.g. Section IIIA above). As a compromise between sampling scaled by the statistics of variability and sampling determined by the importance of known impacts, it is suggested that the initial array density should approximately double from tropics to high latitudes. An array of 3,300 instruments can cover every 3^{o} by 3^{o} location in the global ocean that has depth greater than 2000 m (Fig. 6), while providing the requisite doubling of array density between the equator and 60^{o}N. TOPEX statistics suggest that such an array provides a reasonable ratio of signal to analysis error at high latitudes, where wavelengths of 470 km and longer are resolved, and an even better one in the tropics.

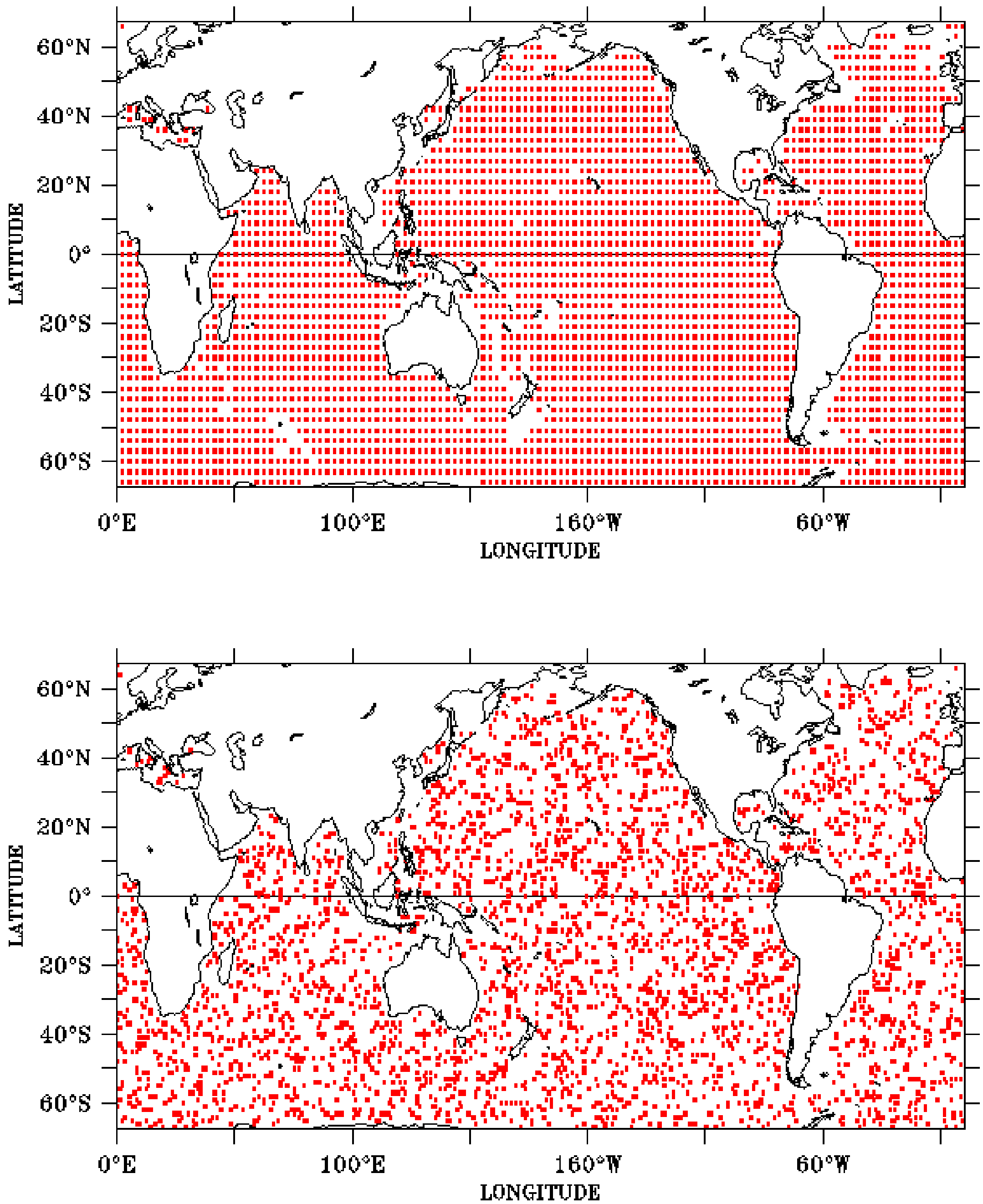

Figure 6. Upper panel – a regular array with 3,300 locations at 3° by 3° spacing with depth greater than 2000 m. Lower panel – a random array of 3,300 locations.

The 3^o by 3^o array satisfies both the requirement for sampling global anomalies in temperature and heat storage (Section IIIa above) and also provides reasonable signal-to-error characteristics for sampling large-scale oceanic variability corresponding to the global altimetric data. Therefore, in the following we will use this spacing as a “straw man” for the Argo array. It is not meant to be the fixed or final configuration of the array, but is a reasonable and practical working design until more information is available. It is a first guess that is consistent with present knowledge of oceanic variability.

It is important to go beyond the simple spectral analysis to show how spatial and temporal averaging can enhance the signal-to-error ratio in resolving known climate signals in the ocean. The procedure here is to identify domains having high (correlated) variability due to the known signals, for example the eastern tropical Pacific domain for the ENSO signal. A time-series is formed of the spatial average of altimetric height over the specified domain. The altimetric dataset is then sub-sampled, with the number of points chosen to simulate a given resolution of an array of “floats”. Here, the tentative Argo density - one float per 3^o by 3^o interval - is used to scale the number of floats in each domain. The location of floats is chosen by random sub-sampling to produce 100 realizations (Fig. 7). The results are used to represent the sampling error of the spatially averaged “float” data with respect to the full altimetric dataset. In these experiments, floats are held at their initial positions. Simulations with moving floats are not greatly different unless the array is systematically divergent. A few examples are discussed below. All calculations use a TOPEX/Poseidon altimetric dataset from the NASA Jet Propulsion Laboratory, including orbital, propagation and geophysical corrections (tides and inverse barometer).

- ***Global change –*** Some of the most compelling climate issues are intrinsically global. Is the global ocean, with its dominant heat capacity in the air-sea-land climate system, warming? How much of the observed global sea level rise is due to steric change, how much to melting of polar ice? Argo will need to measure changes in both temperature and salinity on global scales to directly address these questions.

  Fig. 7a shows the time-series of globally averaged TOPEX altimetric height. Sea surface height apparently increased by 2 cm from early 1993 to early 1998. In the sub-sampling exercise, which uses 3300 randomly placed floats, both the complete and sub-sampled datasets are smoothed in time with a Gaussian filter having a 30 day e-folding time. The sampling standard error for the global mean, with respect to the full dataset, is 0.12 cm RMS compared to the signal standard deviation of 1.2 cm. Fig. 7a shows that, at the level of two standard errors, the hypothetical array is able to observe the annual variability in global sea level (caused by hemispheric asymmetry) and has good resolution of the interannual and longer signals. While part of the change seen in Fig. 7a may be due to systematic altimetry errors from surface wave height, an independent yardstick is the 2 cm/decade long-term increase observed in global sea level stations (Douglas, 1991). A portion of that signal may be steric increase. For reference, either a temperature change of .25^{o}C (at T = 15^{o}C) spread over a depth of 200 m, or a salinity change of .07 psu over the same depth, will produce a 1 cm change in steric sea level. Regardless of the systematic errors in altimetric sea level, the float array will provide a very sensitive measurement system for global steric change.

  A global freshwater signal due to melting polar ice is more problematical to observe than a global warming. For every 1 cm added to the global ocean by melting polar ice, the average salinity in a 200 m layer would decrease by .002 psu. (In other words, the addition of 1 cm of freshwater would raise the pressure at the reference level by the equivalent of 1 cm, but the steric height increase would be only .03 cm). The limitation on observing such a signal in salinity is probably due to systematic measurements errors in conductivity rather than to the sampling errors targeted by the present calculation. Changes in globally-averaged reference pressure are not detectable by Argo. Use of the geostrophic equation (above) to estimate reference pressure leaves an unknown integration constant that is equivalent to the area-averaged pressure. For this reason, in the Jason/Argo combination it is necessary to rely on the satellite altimeters and sea level stations to detect changes in global sea level. However, the successful interpretation of those changes will depend on minimizing systemic measurement errors in Argo, especially of salinity. It is likely that the effects of melting polar ice would be recognized as a regional salinity signal, e.g. in the Southern Ocean, more quickly than in global averages.

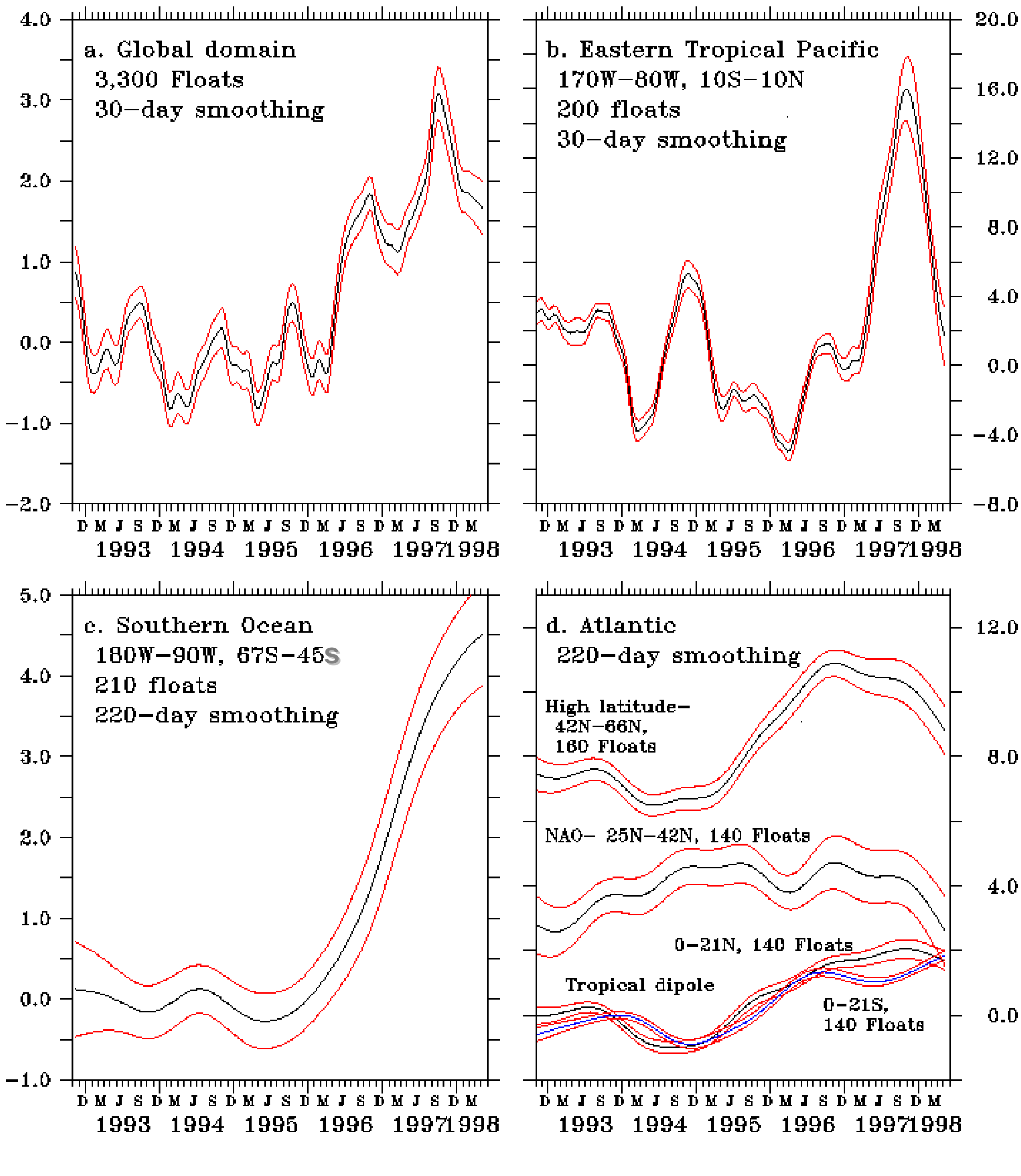

Figure 7. Time-series of spatially averaged TOPEX altimetric height (cm) in the specified domains (black lines). The red lines show (2σ) error bounds on the reconstruction of the time-series using randomly sub-sampled realizations (as indicated in the panels) with average 3^o by 3^o spacing.

The need for altimeters to measure changes in globally averaged sea level highlights another important synergy in the Jason/Argo relationship. Lacking an accurate geoid, the altimeter measures time variability in sea surface height but not the temporal mean. Argo measures the temporal mean but not the global spatial average. Each of the systems supplies vital information missing from the other.

- ***ENSO –*** The strongest ENSO-related changes in sea level are seen in the eastern tropical Pacific, where the domain 170°W-80°W, 10°S-10°N is chosen for illustration, (Fig. 7b). For equivalence to the global case, the domain is seeded with 200 floats. The major 1997 event in the region is seen as an increase in sea level of about 15 cm, with a rapid drop after November of that year. Overall signal standard deviation is 5.3 cm and RMS error is 0.4 cm. The signal to error ratio is excellent in this region. However, this is an instructive example because both temperature and salinity variability were important components of the 1997 climate signal. Expendable conductivity-temperature-depth profiles collected in the region in September 1997 (Fig. 8) showed surface salinity more than 1 psu fresher than normal, with the anomaly decreasing to zero at 100 m. The corresponding steric height anomaly was about 4 cm. The anomaly was seen in 5 XCTD profiles between 10°N and 10°S along a single track at about 125°W and in a second track at about 160°W. The salinity anomaly, due to high rainfall or to inflow of western Pacific surface water, appears to have been of large scale, similar to the temperature anomaly. However, because of the limited sampling, its extent in space and time is not known. An important issue is whether the 15 cm sea level increase was wholly the result of temperature effects or might have included about 25% due to salinity anomaly. If all of the height increase is interpreted as heat content, then a large error could result – about 2°C over a 200 m depth range. Delcroix et al. (1998) also found large changes in the western Pacific warm pool during the 1996-97 event, with peak-to-peak variations of 1.6 psu. The *Argo* and other arrays would resolve these issues by identifying the individual contributions of temperature and salinity to sea level, with sampling errors less than 0.5 cm. Aside from being a dynamic contributor to sea level, the strong salinity signals accompanying ENSO may also have thermodynamic consequences in regulating air-sea heat exchange (e.g. Lukas and Lindstrom, 1991). A comprehensive climate observing system must include salinity.

- ***The Southern Ocean Wave –*** A propagating signal in sea surface temperature, sea ice extent and meridional wind stress in the Southern Ocean was described by White and Peterson (1996). The signal has a wavelength of half the Earth's circumference and a period of 4-5 years. Largest amplitudes (> 0.5°C in SST) are seen in the domain, 180°W-90°W, south of 45°S, and this is the domain chosen for the TOPEX study (Fig. 7c). The domain is seeded with 210 floats. The time-series are filtered to suppress annual and shorter period variability (using a Gaussian filter with 220-day e-folding) and to increase the signal-to-analysis error ratio for interannual variability. The previous maximum in SST described by White and Peterson (1996) occurred in 1992 in this domain. Therefore, the increase of 4.5 cm during 1996-98 lags slightly the expected phase of maximum SST in the circumpolar wave. In this example, it is not probable that the sea level signal is mostly due to near-surface warming. The thermal expansion coefficient of seawater is strongly dependent on temperature, and is only one-fourth as large at 1°C as at 20°C. At 1°C, a warming in a 200 m thick layer of 1°C produces only a 1.3 cm steric height increase. The observed sea level rise may include contributions from depth-independent pressure response to wind forcing, from meandering of the circumpolar current and from melting/freshening. At any rate, the sea level signal is large and interesting, and its underlying oceanographic causes should be readily detectable by the Jason/Argo combination.

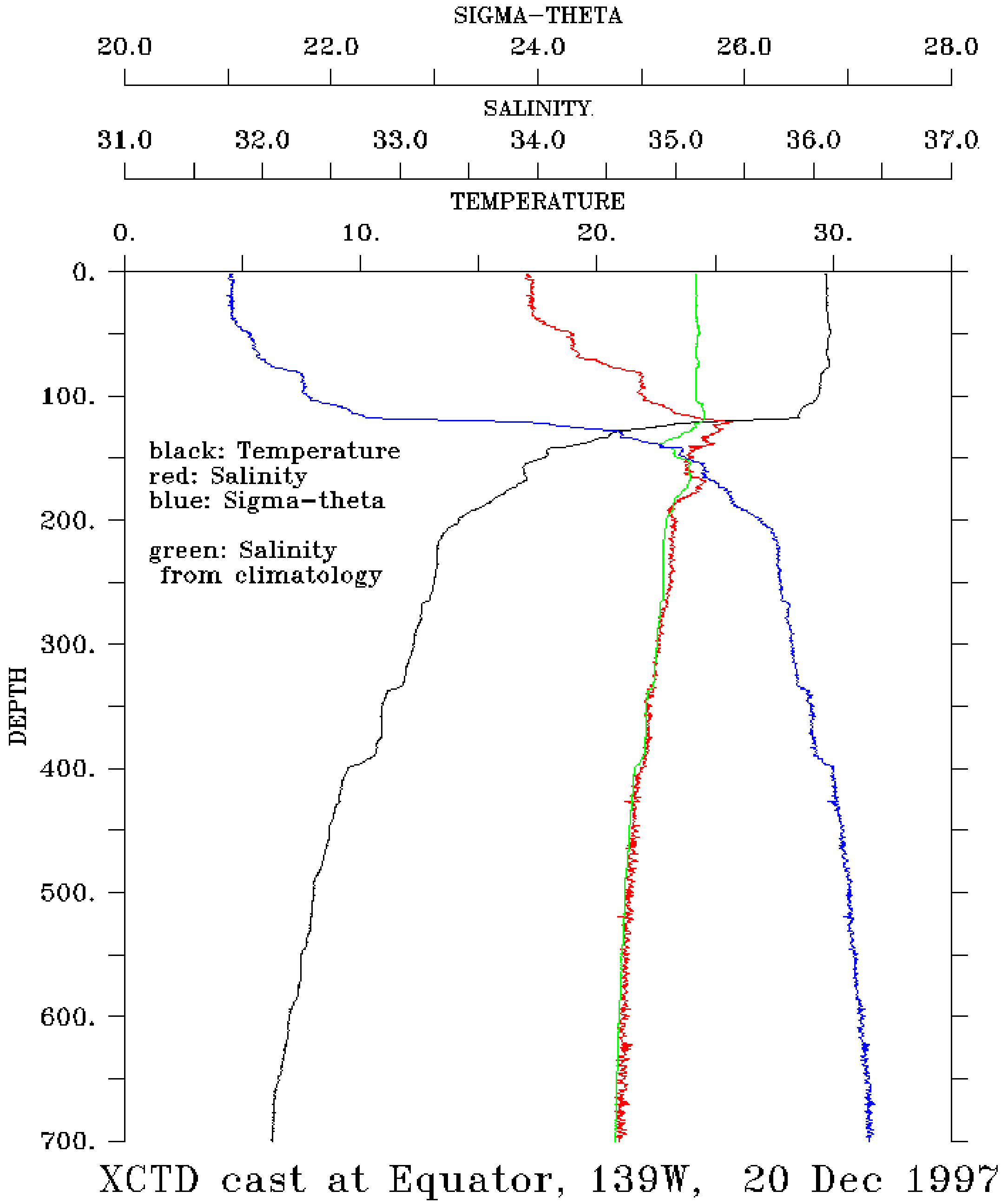

Figure 8. A single XCTD profile showing measured salinity (red) and climatological salinity (green) at the same location. Additional XCTD drops showed the fresh anomaly to be spread from about 10°N to 10°S and to occur in a transect at about 160°W as well as at 125°W. The existence of this fresh anomaly had a substantial effect on sea surface height (several cm) and hence on the interpretation of the TOPEX altimetric data during the 1997 ENSO episode.

- ***North Atlantic Ocean variability –*** Signatures of a number of climate signals have been identified in the Atlantic Ocean. Here, the Atlantic is divided into a series of domains corresponding to known oceanic signals. These are labeled in Fig. 7d as "high latitude" (42^{o}N to 66^{o}N), "North Atlantic Oscillation" (25^{o}N to 42^{o}N), and tropical Atlantic dipole (21^{o}S to equator and equator to 21^{o}N). Temporal smoothing is again applied to each time series to suppress annual variability and to increase interannual signal-to-analysis error ratios. Each of the domains shows sea level signals of several cm, with sampling errors sufficiently low that the signals are well resolved by the given array.

  Another Atlantic problem of great interest is the overall heat budget of that ocean. Northward heat transport is large in the Atlantic, about 1.1 +/- 0.3 x 10^{15} W on average across 24^{o}N (Hall and Bryden, 1982, MacDonald and Wunsch, 1996). The variability of that transport, and of the underlying thermohaline cell of the Atlantic Ocean are not known. Although both ocean heat transport and air-sea heat exchange are difficult to measure with high accuracy, the heating/cooling of the ocean that is the residual of these two processes can be measured very well. The TOPEX dataset shows an increase in sea level north of 24^{o}N of 2 cm between 1993 and 1996. If that signal is interpretable as warming, it represents a temperature change (at 15^{o}C) of 0.5^o averaged over a layer 200 m thick, or a heating of 5 W/m^2. The TOPEX sub-sampling calculation indicates an error in the height change estimate of 0.4 cm or, equivalently, 1.0 W/m^2. Over interannual to decadal time-scales, heat and freshwater storage terms can be measured with high accuracy, far better than the capability to observe either heat transport or air-sea exchange. While it is important to know all components of the heat and freshwater budgets, the storage term represents the net effect of climate change. It is a fundamental measure of the evolving state of the climate system and of the ocean's capacity for driving variability in the atmosphere.

In each of the above examples, and in others that were examined, the spatial and temporal averaging enhances the signal-to-analysis error ratio with respect to the non-averaged fields. The known climate-relevant signals in the ocean, with large spatial scales and seasonal to decadal time scales, can be adequately observed with a broad-scale array if the mesoscale variability is appropriately suppressed by smoothing.

C. Using Argo to measure absolute pressure in thermocline and intermediate waters

In parts A and B above, the design problem is focused primarily on measuring anomalies in temperature and salinity on broad spatial scales. An additional important objective of Argo is measurement of ocean circulation in order to determine the broad-scale fluctuations in advection of temperature and salinity. Analyses of broad-scale XBT data (Deser et al, 1996) show propagation of thermal anomalies in the subtropical thermocline. Models (e.g. Gu and Philander, 1997) suggest that advection by interior gyre circulation may be an important mechanism in decadal variability. Argo should be capable of detecting not only anomalies in property distribution but also in the transport of these anomalies by the large-scale circulation.

Estimation of geostrophic velocity at any level requires knowledge of the velocity at a reference level, plus the density field as a function of depth. In principle, the reference velocity can be either at the sea surface, from altimetry, or at depth from the float. The thermal wind equation relates the velocity at an arbitrary depth to the reference velocity,

$$u(z) = u_{ref} - \frac{g}{f\rho}\int_{z_{ref}}^{z} \frac{\partial \rho}{\partial y} dz \quad , \quad v(z) = v_{ref} + \frac{g}{f\rho}\int_{z_{ref}}^{z} \frac{\partial \rho}{\partial x} dz$$

with the float profile providing the required density information to integrate from depth z_{ref} to z.

During WOCE, over 300 floats were deployed to measure the reference velocity field in the tropical and South Pacific (Fig. 9, from Davis, 1998). The array provided over 10,000 individual estimates of flow at depths near 900 m. Davis (1998) was able to map the time-mean geostrophic pressure field (Fig. 9), but the array was too sparse to estimate the time-varying pressure. The number of observations was inadequate to determine the statistics of the pressure field on small spatial scales. However, substantially different covariance functions produced very similar large-scale maps of pressure.

The WOCE Pacific array yields important conclusions. First, in order to map the time-varying pressure field, a considerably denser array is required. The hypothetical 3^o by 3^o Argo array is approximately 5 times as dense as the WOCE Pacific array. With a five-fold increase in the density of observations, the same covariance information used to construct Fig. 9 indicates that 1-year averaged pressure maps would have errors of 1.3 cm on spatial scales of 700 km and longer. At this level of accuracy, estimation of absolute geostrophic velocity at intermediate and thermocline levels will be more accurate if integrated upward from the mid-depth reference level (say 1500 m), than downward from altimetric height of the sea surface. An Argo deployment at 3^o by 3^o spacing would provide both the capability to map low frequency variability of ocean circulation and the additional statistical information needed to further improve the network design.

D. Designing Argo to monitor climate signals

Argo will be a critical element for continued observation of large-scale variability in ocean thermohaline characteristics. It will provide essential data for the estimation and monitoring of heat storage. A number of substantial large-scale changes have been described in the Pacific and Atlantic Oceans using WOCE and pre-WOCE hydrographic datsets (e.g. Parilla et al, 1994, Joyce and Robbins, 1996, Lazier, 1995, Bindoff and Church, 1992, Johnson and Orsi, 1997). It is crucial to obtain complete descriptions of the evolution of these and other climate-relevant signals in the ocean in order to understand the role of the oceans in the climate system. Repeating hydrographic sections will continue to be needed to sample the abyssal ocean and to provide the highest quality reference measurements. However, Argo can provide for the first time a truly global and continuous monitoring of change in the upper 1500-2000 m. An appropriate design criterion for Argo is that its resolution be adequate to describe the further evolution of signals already seen in the WOCE and pre-WOCE data.

As an illustration of the Argo contribution, the upper panel of Fig. 10 shows the large-scale temperature change observed along the 24°N Atlantic section between 1981 and 1992 (see Parilla et al., 1994). The figure was obtained from two hydrographic transects having station spacing between 50 and 100 km. This dense sampling was used to filter out the mesoscale signal and estimate the large-scale temperature difference. The two hydrographic datasets were then sub-sampled every 3^o of longitude to obtain Argo-like spacing, and the differences were re-calculated. Obviously in this case, it is more difficult to filter out the mesoscale signal. Nevertheless, the main features of the temperature difference are already rather well recovered (lower panel). By invoking temporal as well as spatial averaging, Argo will actually provide a mapping with better accuracy than can be obtained from individual hydrographic surveys. *Argo* sampling at 10-14 day intervals will allow many independent realizations of the eddy field to be averaged in a period of a few months, in order to estimate the large-scale field. Thus, Argo is an appropriate strategy to exploit the legacy of WOCE and observe the interannual to decadal signals in all of the oceans.

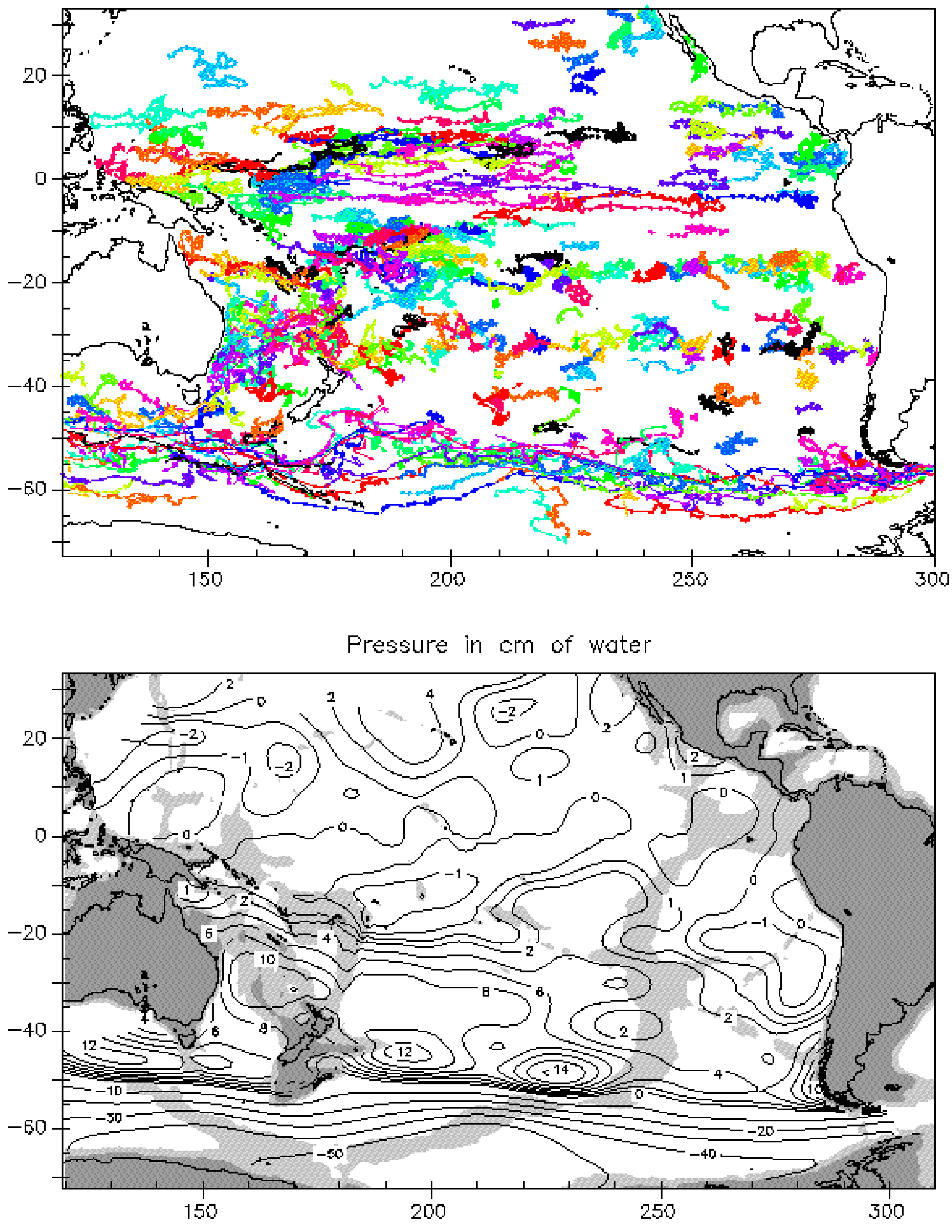

Figure 9. Upper panel – trajectories of more than 300 floats deployed in the Pacific Ocean during WOCE at about 900 m depth (Davis, 1998). Lower Panel – absolute pressure field at 900 m depth derived from the float trajectories (Davis, 1998)

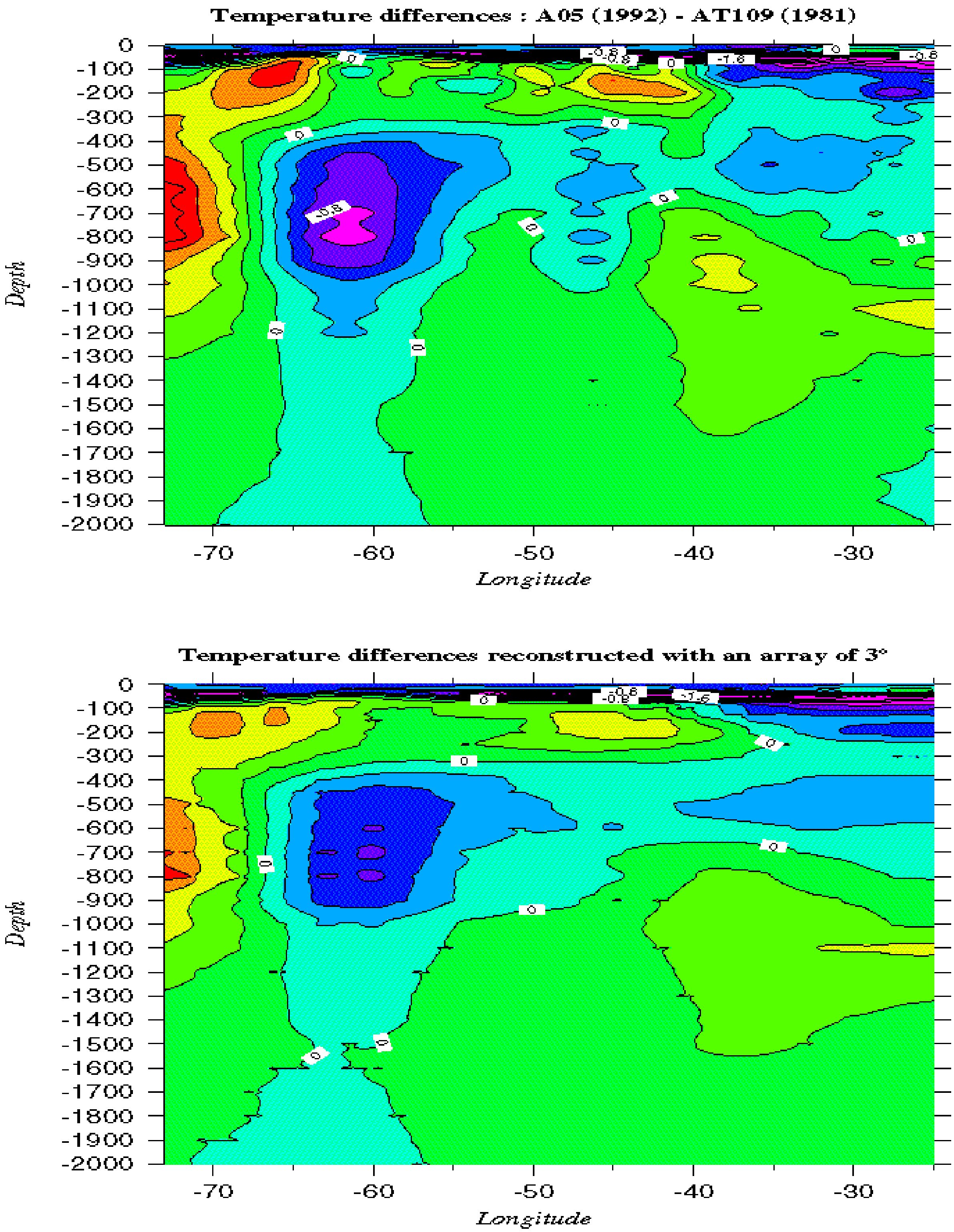

Figure 10. Upper panel - Large scale temperature differences between two hydrographic transects (A05 - 1992 and AT109 - 1981) in the North Atlantic (24°N) (Parilla et al., 1994). Contour interval is 0.2°C. Lower panel - same as upper panel but with transects subsampled at one data point every 3 degrees.

E. The needs for Argo in testing and constraining ocean and coupled models of the climate system

To be most useful for ocean modeling and ocean state estimation, the Argo float network needs to sample the ocean's large-scale dynamical and thermohaline processes. Details of actual system implementation and sampling density therefore depend fundamentally on the processes present in the ocean. It is clear from the above discussion that eddy statistics are significantly inhomogeneous as are the physical processes themselves, leading to different sampling requirements, e.g. in high latitudes, as compared to the subtropics or the tropics. The requirements here for limiting aliasing by the eddy field are analogous to the discussions above, but in this case it is the large-scale physical processes that require adequate resolution. The following discussion is aimed at illuminating this issue.

The approach taken to network design in this section is through simulation of the ocean using a state-of-the-art general circulation model and subsequent analysis with respect to a data hierarchy and data sampling strategy. This approach allows one to sample the model "truth" in a way that is more complete than is possible for the real ocean. These results will complement the above data-oriented studies.

A status report on numerical studies needed in support of Argo system design is presented below. But first, the benefits of an improved observing system in constraining ocean and coupled models of the climate system are discussed. The following is a summary of the ways that an in-situ observing system will enhance ocean modeling and ocean state estimation, with specific emphasis on Argo.

- ***Model testing -*** Model-data comparison studies have indicated that adiabatic processes are relatively well represented in state-of-the-art ocean general circulation models (OGCM's). Various examples (e.g., Fu and Smith (1997); Stammer et al. (1996)) illustrate that over a large geographical extent the models accurately simulate the observed phase speed of planetary wave motion. This is especially true in lower latitudes and in the Indian Ocean, where the observed wind-forced changes of the circulation are reproduced with surprising agreement in phase. Wave amplitudes tend to be low. In middle and high latitudes, discrepancies in the simulated wave structures may be attributed to errors in the operational wind stress fields.

Major discrepancies in present circulation models reside in the representation of diabatic processes and in the simulation of the effects of eddies on the large-scale circulation. Physical processes related to boundary layer formulations at the surface, the lateral boundaries, and the benthic boundary layers are not accurately represented or missing. Water mass formation processes and the ventilation of the interior ocean are insufficient - partly in combination with erroneous boundary conditions at the surface or at artificial lateral boundaries. Uncertainties in the representation of mixing processes in the interior ocean are related to this problem as well. Moreover, the advective processes in low latitudes and in boundary current regimes are sensitive to details in the model resolution. The effect of model resolution and of details in eddy parameterizations on modeling of ocean circulation on climate time scales is unclear.

The advent of high-quality altimeter data led to significant developments in testing and improving OGCM's because, for the first time, model and data variability could be compared over a range of frequencies and wave numbers that had not been observed previously. For a similar step in model improvement with respect to diabatic processes, in-situ data with sufficient space and time coverage to be complementary to altimetry are required to address the shortcomings indicated above. A float network will serve as an essential step in that direction. Without the required model improvements, coupled ocean-atmosphere circulation models will not be sufficient to address the scientific challenges of the next decade.

- ***Temperature and Salinity Covariances -*** The information about temperature and salinity covariances in the ocean is a fundamental prerequisite for ocean state estimation. However, this information is of importance in its own right since it provides a very basic description of ocean variability and its relation to atmospheric forcing. Previous sampling of the hydrographic fields in the ocean is not sufficient to determine covariances of temperature and salinity globally. This information is required to quantitatively understand climate-related variability in the ocean. Any change in the surface heat flux will inevitably lead to a change in the ocean temperature field and heat content. Likewise, the lateral import of ice or a changing surface freshwater flux will modify the surface salinity budget and the interior stratification. Details of the horizontal scales and depth dependence of oceanic response to those anomalies are unclear. The errors in present models in the representation of respective adjustment processes are unknown. A global hydrographic network designed to sample the ocean roughly every 10 days (similar to present altimetric sampling) will allow these issues to be addressed.

• ***Model Initialization -*** Given the sparseness of ocean observations, the best available datasets are still unacceptable for initializing ocean models. Dynamically consistent T and S fields are required, with known errors that are sufficiently small to have negligible impact in model solutions. Argo can make a large contribution by providing both T and S globally with sufficient spatial and temporal resolution of the upper ocean. The deep ocean, which has longer time scales, is also important and needs to be sampled by other elements of the global observing system. It should be recognized that salinity is a vital element that needs to be measured simultaneously with temperature if the goal is to provide dynamically consistent initial conditions for ocean models. Ultimately, an estimate of initial conditions for climate models needs to be obtained in the framework of ocean state estimation summarized below.

• ***Ocean State estimation -*** The impact of a global profiling float program on ocean state estimation is very broad, from providing prior process and error statistics, to providing data required to test solutions, to actually constraining the solution itself.

To produce an estimate of the time-varying ocean circulation from diverse remote and in-situ data, individual data sets need to be weighted according to their specific error covariances. For sea surface height, present global ocean state estimation uses observed eddy statistics, as well as global geoid error covariance matrices, as provided by the geodetic community. However, the respective information is missing for most other data sets, including surface meteorological forcing fields and subsurface T and S. Because surface fluxes and interior hydrography are intimately linked in a complex way over a broad range of scales, it is important to understand both of them to obtain both a consistent estimate of the ocean's state and an understanding of ocean dynamics involved in long-term climate processes.

Presently, global ocean state estimation experiments are mainly constrained by surface altimeter data. Those data induce changes in the model over the entire water column. An example is shown in Fig. 11. The figure is taken from a global state estimation (Stammer et al., 1997) in which an OGCM was constrained (1) by one year of absolute TOPEX/POSEIDON sea surface height relative to the EGM96 geoid model, (2) by the time dependent T/P sea surface height, (3) by 10-day averages of NCEP surface fluxes of momentum, heat and fresh water, and (4) by the annual mean Θ-S climatology. The model is forced to consistency with those data by using the model's adjoint to modify initial temperature and salinity fields over the full water column, and to adjust the meteorological forcing fields. The figure shows in its top panel the model meridional velocity at 25^{o}N in the Atlantic Ocean for September 1993. Middle and lower panels show the respective changes in meridional velocity and temperature, imposed by the T/P data over the full water column. Both fields need to be tested as a function of time and constrained better than by altimetry alone, e.g. to improve meridional heat flux estimates. Salinity again will be an important factor making an Argo system superior to XBT measurements.

Longer and more sophisticated assimilation runs are underway globally and regionally. They all are hampered by the lack of in-situ hydrographic data that would allow an efficient way of finding the equilibrium between the interior hydrography, the surface altimeter data and surface heat and freshwater boundary conditions. In terms of hydrography, models are usually constrained by the Levitus monthly hydrographic climatology, but interannual variations in the ocean are significant and deviations from Levitus can be large. The requirement is for time-varying hydrographic fields that are analogous to available sea surface altimeter and SST data. It is especially the combination of T and S profiles, anticipated by an Argo system with high temporal resolution, which could lead to a significant improvement above the present situation.

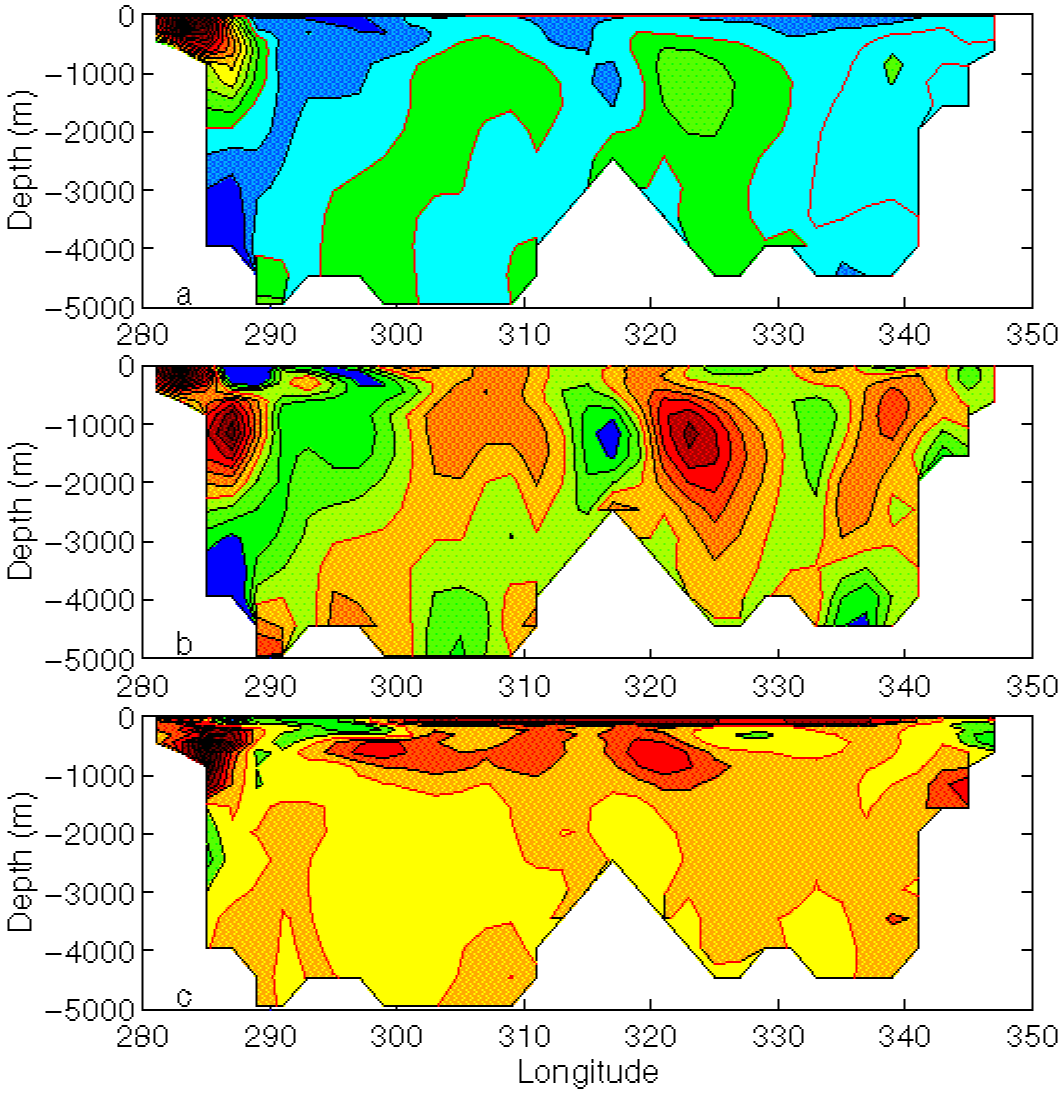

Figure 11. Zonal section along 25°N in the North Atlantic of the estimated meridional velocity component (a) during the 10-day TOPEX/POSEIDON repeat cycle 29 (early July 1993). (b) and (c) show the corresponding changes in meridional velocity and temperature of the constrained (by T/P) model relative to the unconstrained model along the same section, respectively. Contour intervals are 1 cm/s, 0.4 cm/s, and 0.2°C, respectively. The red lines mark the zero contour in all panels.

The salinity data will provide important information for describing the hydrological cycle of the ocean and for determining the net freshwater exchange at the surface. Historical evidence that low salinity anomalies in the upper ocean at high latitudes have "capped-off" the thermocline, preventing deep convection and limiting heat loss from the ocean. Such anomalies (ie., the "Great Salinity Anomaly described by Dickson et al., 1988) are advected around the subpolar gyre of the Atlantic and appear to be related to decadal time-scale climate anomalies.

Beside T and S profiles, Argo will provide the additional information about the flow field at the target depth of the float. That flow field needs to be used for model testing and ultimately will be part of the state estimation procedure. Equally important, a profiling float system obtains important T and S observations in the surface layer of the ocean, which is required to improve our understanding of near-surface processes and the interaction of the ocean with the atmosphere. Presently fields of sea surface temperature data are included in state-of-the-art ocean estimation procedures to improve sea surface heat flux estimates and sea surface temperature estimates. Note that the latter is of fundamental importance for understanding air-sea gas exchanges and carbon cycling. However, sea surface salinity observations are available only along a few VOS lines. The anticipated sea surface salinity information from ARGO will be unprecedented for improving our understanding of the hydrological cycle over the ocean, which is directly related to the release of latent heat into the atmosphere.

- ***Modeling studies needed for Argo design -*** In the following, we will discuss specific design requirements for Argo in the context of support for ocean and climate modeling. The approach focuses on the impact of the ocean eddy field on sampling requirements, and on optimal vertical profiling to capture climate signatures. It is clear that such an approach needs to be based on an eddy-resolving model to be able to simulate eddy statistics and Lagrangian trajectories of floats over a 2-3 year time frame. Such a model will be seeded by synthetic particles that sample the model in a way similar to the anticipated Argo system. The outcome of the study will shed light on the following questions:

1) How many instruments are required to adequately observe large-scale climate signals?
2) At what depth should a float array reside (shallow or deep) to cover the global ocean in the best possible way (clustering effects)?
3) How deep do profiles need to be sampled to successfully capture climate signals and to fully complement altimetric surface height observations?
4) What additional or alternative measurements are required or preferred?
5) What is the effect of float residence time in the surface layer on the general float dispersion?
6) What are the differences of Eulerian versus Lagrangian time scales?

The original particle distribution will be on a regular grid with target depth ranging from 300 m to 2000 m. Every week the floats will ascend to the surface layer, reside there for 0-12 hours, then return to their target depth and continue to drift subsequently for the next week. The impact of surface residence time on the dispersion of the float array is a question of importance. Each time a model float rises to the surface the full water column will be sampled with respect to T(z), S(z), and velocity, with the profiles stored for further analysis. Also stored will be time-series of the model state along the float trajectory, and monthly fields for subsequent evaluation.

The model output will also be used to study characteristics of sea surface salinity and their representation by individual floats. This analysis is intended for potential future satellite missions intended to measure surface salinity anomalies on spatial scales of about 100 km and larger and the possible use of point-wise float measurements for calibration purposes.

To describe an example, a 1/6 degree version (or higher) of the MIT North Atlantic model will be used to simulate floats at three depth levels, with seeding on a 1 degree regular (or random) grid. The model will be driven by daily NCEP surface fluxes that were adjusted by a global data assimilation procedure in such a way that global TOPEX/POSEIDON altimeter data were optimally simulated by the model. The model will be spun up for some time until a statistical near-equilibrium is reached. Floats will be seeded and then advected by the model flow field.

Presently, numerical Argo design experiments are being proposed or carried out in France, the U.S. and Australia. Because of the required high model resolution, the efforts are substantial. Although detailed results are not expected for about a year, the anticipated infomation will be valuable to confirm or refine the answers obtained from data-based studies. Because the Argo design will be evolutionary, results obtained from the numerical approaches will influence the design process as they become available.

F. Other elements of a comprehensive ocean observing system

As was noted above, the *Argo* network is proposed as a major enhancement of and contribution to an integrated global ocean observing system; it is not the complete system. This document focuses on *Argo* to emphasize the new capability for global *in situ* observations. Moreover, special attention is needed because *Argo* requires substantial resources and commitments to bring it into reality. This should in no way diminish the attention given to other critical elements of an ocean observing system for climate. Rather it should help to re-focus attention by raising the capability of the complete system. The climate observing system has been the subject of a number of comprehensive studies including those by OOSDP (1995) and CLIVAR (1998). In addition to *Argo* and other methods for sampling the upper ocean, and to the satellite observations of the sea surface, other important elements of the ocean observing system include:

- Measurements of air-sea fluxes of momentum, heat, and water
- Measurements of western boundary currents, the equatorial waveguide, and other small-scale features
- Measurements of the abyssal ocean
- Measurements of biological and geochemical properties
- Local or regional process experiments

Argo does not address these needs. It is a global broad-scale network, measuring the physical state variables of the upper ocean. However, the existence of Argo will greatly increase the scope of the climate observing system and will provide the large scale context needed to justify many additional elements of the system.

IV. The Implementation of Argo

Implementation of the Argo network is a balancing of the scientific requirements described above with the practical issues incumbent in the instrumentation of remote regions and hostile environments with an array that is unprecedented in scope and magnitude. A number of key scientific, technical and practical issues intersect in a discussion of implementation. As with the design problem, this is an evolutionary process, and the following describes the present view of the most pressing implementation issues. Although there are significant problems to overcome, it is useful to remember the alternative to Argo. Continuation of the present sparse and fragmented observing system, with poor accuracy and coverage and without systematic salinity sampling, would delay progress in climate research and other arenas for many years into the future.

In the following, it is assumed that the array is global, with spacing of approximately 3^{o} (Section III). Float cycle time is approximately 14 days and float lifetime is 100 cycles. Issues to be addressed by the Argo Science Team in the near future are listed in italics.

- ***Deployment techniques –*** At this time, profiling floats have been deployed successfully from research vessels and ships of opportunity. It is likely that air deployment will become feasible in the near future. The oceanographic community has experience and success in deploying global observing arrays. In particular, the global surface drifter network is maintained through deployments from research vessels, merchant ships and aircraft. Fig. 12 shows the method of deployment for surface drifters deployed during 1997 and 1998. Another good indicator of the global potential for Ship of Opportunity deployments is in the distribution of XBT data, Fig. 2. Even in remote areas of the globe such as the Southern Ocean, there is sufficient merchant and research vessel traffic to maintain much of the global drifter array and of a global profiling float array.

A successful demonstration of air deployment is needed.

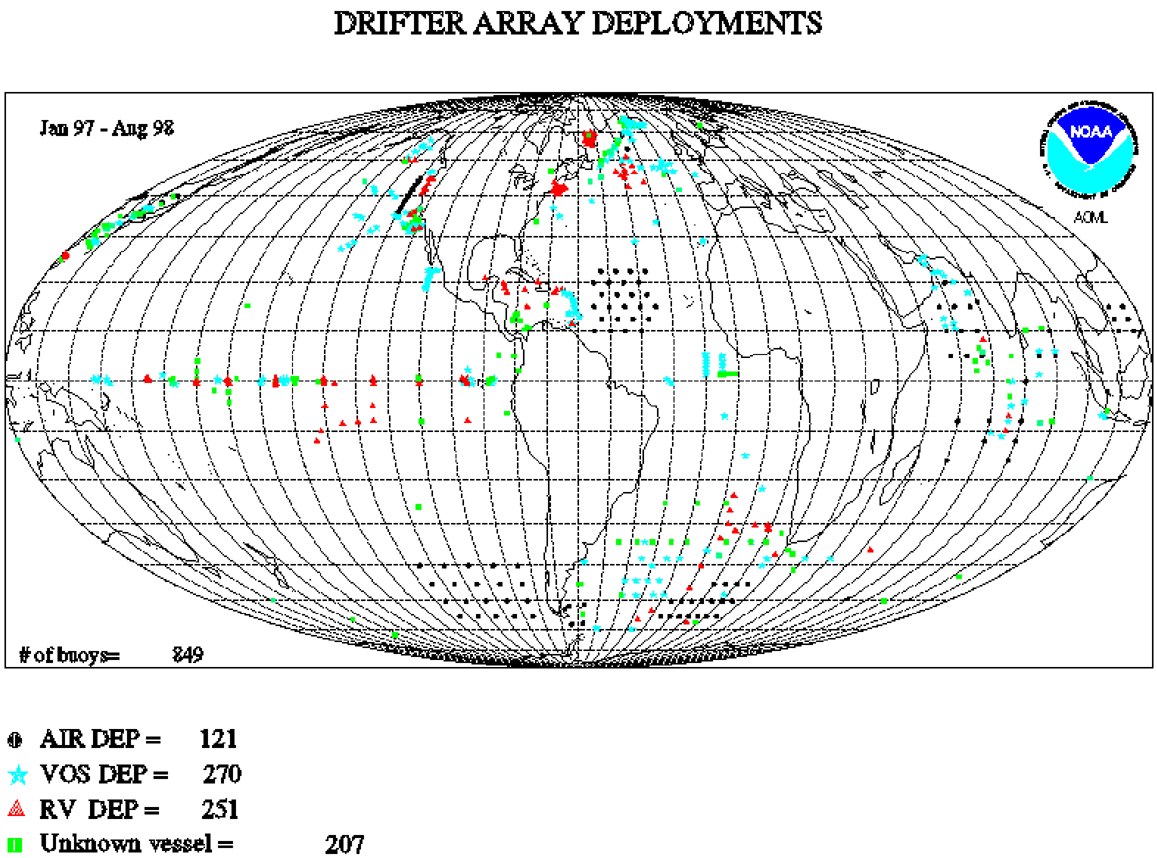

Figure 12. Deployments in the global surface drifter array during Jan 1997 – Aug 1998.

• ***Deployment strategy –*** Present arrays of profiling floats are in the North Atlantic and eastern tropical Pacific Ocean. Because of the ongoing work and the high scientific interest in those areas, it is suggested that the global array be implemented by expansion from those two initial “foci”. Additional foci in the Indian Ocean and Southern Ocean should be established as soon as practical. The detailed deployment strategy should be negotiated by the international Argo partnership via the Argo Science Team, by matching the resources and needs of the contributing nations with the strong requirement for a global array. Initial deployments of Argo floats should begin in the year 2000. It will be necessary to achieve the steady-state deployment rate of about 825 floats per year within a couple of years if the GODAE objective for a global array by 2003 is to be achieved. Although the target is for a completed array by 2003, the time is very limited, and some regions of the global ocean are bound to provide substantial logistical challenges. A massive multi-national effort is required, with major coordination and implementation hurdles. If the target proves impractical, then an acceptable fallback is a global array at reduced resolution in 2003, with a completed array by 2004 or 2005.

In a given region, problems of logistics and accessibility should be balanced against the advantages of regular redeployment. As long as stability of salinity sensors remains an issue, it will be desirable to have instruments of more than one age in a given region, to compare salinity from “new” and “old” instruments. A strategy of phased redeployment would also prevent large gaps in the array from opening if instruments expire before they can be replaced. It is therefore recommended to deploy in a given region at 50% of the final density, and then to deploy the next 50% two years later. A redeployment of 50% of the floats in a region every 2 years would then be needed to maintain the array.

The Argo Science Team should assess and coordinate individual and national commitments with the aim of ensuring global coverage and adequate resolution. The team should assist with negotiations to resolve potential gaps and overlaps in the array.

• ***Communications*** – The present communication system allows one-way transmission of T/S data from about 80 depths per profile and precision of about .01 in temperature and conductivity. Messages are transmitted multiple times and floats remain on the sea surface for about a day to ensure successful reception. Communication uses about 50% of a float’s energy budget. There are presently several viable possibilities for upgrading the communications system, including the nearly completed global cellular systems. Requirements are for two-way communications, a decrease in redundant transmissions and a lowering the time at the sea surface to minutes. The latter is important to prolong float survival and to minimize the tendency of the array to clump or scatter due to surface velocity. With two-way communications, more data can be transmitted with lower power requirements. Profile data should be transmitted at 2 m intervals vertically with precision of .001. It is too early to determine which communications system will be used. A secondary objective of two-way communication is to allow modification of float mission parameters, for example to keep a float on the sea surface for recovery.

The status and cost of competing communications options should be reviewed by mid-1999.

• ***Parking/profiling depths*** – The initial profiling depth of 1500 m is based on practical considerations. The goal is to reach as great a depth as possible without compromising the requirement of 100 cycles per float lifetime. A profiling depth of 2000 m will provide substantial scientific benefits, and should be adopted when feasible. The float parking depth should be at the base of the profile, rather than at a thermocline or shallow depth, to minimize the tendency for the array to be clumped or scattered by the velocity field, and the resulting sampling bias.

• ***Data assembly and quality control*** – Real-time delivery, and wide accessibility, are key principles of the *Argo* proposal. As much as is possible, participants in the global array should take responsibility for all phases of their floats’ lifetime, including assembly and/or preparation/checkout, deployment, communications, quality control, data assembly and scientific analysis. Detailed knowledge of and participation in the complete float history is the best assurance of a consistently high quality product.

Quality control should consist of two or three phases. The first phase should be fully automated to ensure completion within a day or two of data collection. The automated phase should consist of data checking and flagging based on (1) comparison to climatology, (2) comparison to objective interpolation from nearby neighbors and (3) comparison with the float’s previous cycles. On completion of automated quality control, data should be distributed on the real-time network and moved immediately to data assembly centers. The second phase may involve inspection of individual profiles and subjective judgement. In addition to subjective review and repetition of the previous checks using an expanded dataset, this phase should also include flagging based on data acceptability in GODAE assimilations. Phase two quality control should be completed within three months of data collection. A third phase will be required (with a lag of years) in regions where substantial data are required to update climatological and statistical information.

The Argo Science Team should make specific recommendations of quality control procedures and on the pathways for data flow to ensure real-time availability of good quality data.

• ***Salinity drift -*** The drift of salinity sensors is a significant technical issue facing the Argo network. There is active work in several institutions to determine the best among presently available sensors, to modify float design for better lifetime of sensors, and to develop new sensors with improved long-term stability. Additional work is to determine the potential accuracy in recalibration of sensors using T/S characteristics of deep water masses. Present capabilities in salinity measurement are sufficient for large-scale deployments, but there is potential for improvement in the near future. An example of the present capability is shown in Fig. 13, from a float deployed for the past year and still operating in the western subtropical North Atlantic (upper panel). The lower panel shows the unedited T/S data from 36 profiles by this instrument, overlain on historical data from the same region. Within the thermocline, where the T/S relation is most stable, salinity variation is less than 0.01 psu. The scatter in the float data is less than in the historical database. Above and below the thermocline, natural variability is greater.

The Argo Science Team should track and encourage development work in order to ensure that the most stable systems for salinity are included in early deployments.

V. Summary

Argo is a project dedicated to delivering a major enhancement to the upper ocean (0-2000 m) temperature and salinity sampling network. The original "prospectus" and a draft of this Plan have been reviewed by a wide-range of scientists, both advocates and non-advocates, with the overwhelming consensus that *Argo* is an appropriate, and much needed, initiative. *Argo* is part of a major revolution in sampling of the ocean which includes the TAO array in the Pacific, satellite altimetry and, now, autonomous profiling floats. It is presented as a method that complements other direct and remote sampling approaches.

Argo is an initiative of GODAE and CLIVAR, but should be regarded as a contribution to the wider body of research and operational activities. The operational phase of GODAE, 2003-2005, is targeted as the period when *Argo* should reach its full configuration.

This paper presents some initial ideas on the design and implementation of *Argo*. The design is founded on experience in both TOGA and WOCE and, in particular on experience with the broad-scale XBT network and the precision altimetry provided by TOPEX/POSEIDON. Data upon which to base design studies is limited and so *Argo* must plan for continual re-assessment and evolution of its design as better and more comprehensive information is available. Altimetry is highlighted as a particularly important, complementary data stream, and the dual systems of *Argo* and *Jason* as key elements of the global observing system of the next century.

Based on the information available now, it is proposed that *Argo* should comprise around 3300 floats, each profiling through 0-2000 m around 25 times per year over an estimated lifetime of 3-4 years. Each float will measure both temperature and salinity and will provide estimates of current velocity at the parking depth of the floats (probably around 1500 m). All data will be telemetered in real-time and will be available (and widely distributed) within 1-2 days of capture (or sooner if practical). The quality of the data will be ensured through the establishment of data assembly centers for float data.

Many model and scientific studies are need to guide the development and implementation of *Argo*. It is also clear that *Argo* data will be most effective if it is integrated with other measurements of the ocean, both remote and direct, and interpreted with the aid of models and data assimilation.

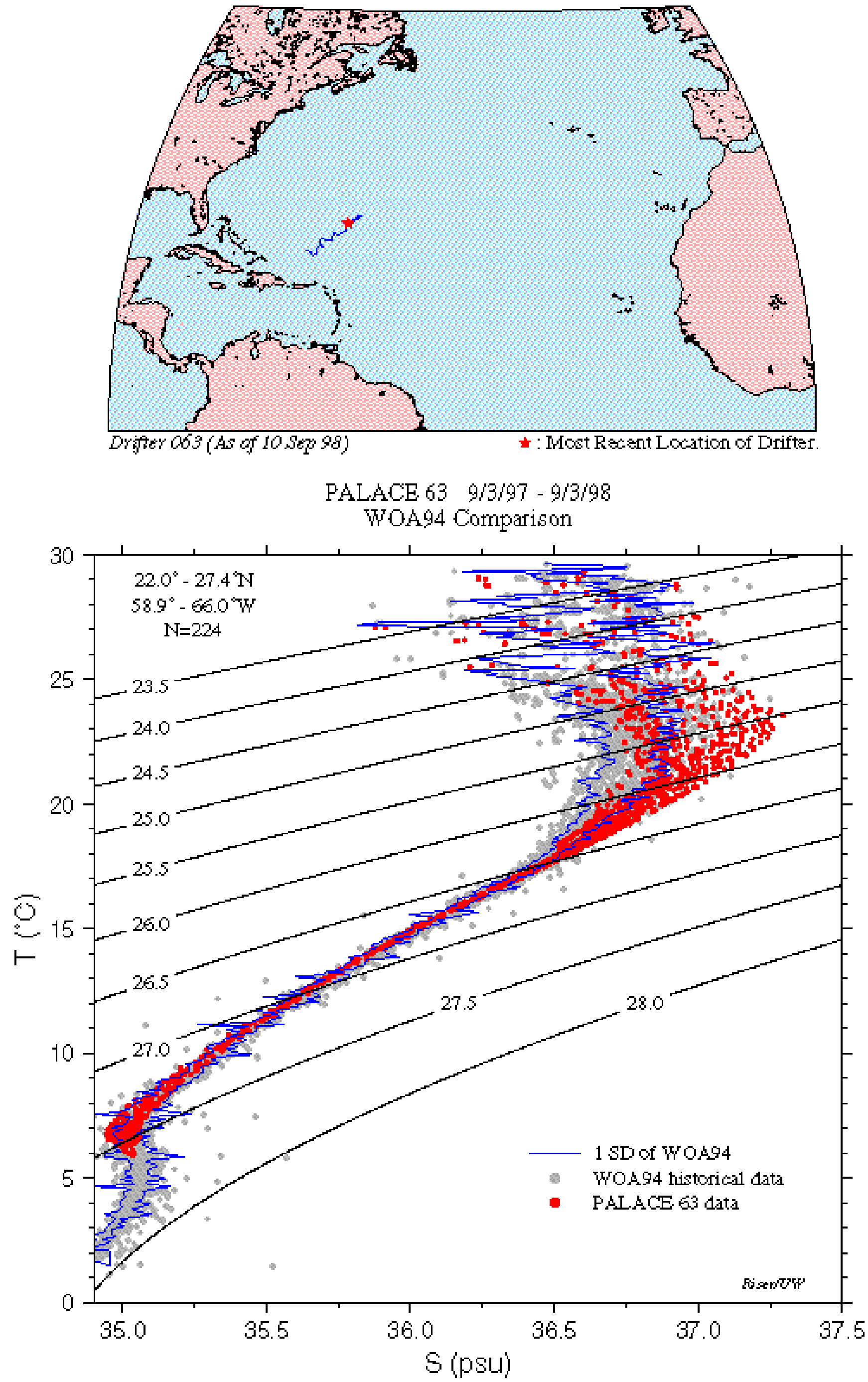

Figure 13. Upper panel – Trajectory of a float in the western subtropical North Atlantic from September 1997 to September 1998. Lower panel – T/S data (red, unedited) from 36 float profiles along the displayed trajectory. Also shown is historical data (gray) from World Ocean Atlas 1994 in the same region.

Deployment strategies will be a focus of the *Argo* science team in the short-term. It is clear global coverage will not be easy to achieve and it is likely a consortium-like approach will be needed to ensure adequate sampling in data sparse regions. There are also several outstanding technical issues that need to be addressed. However, our best advice at resent suggests none of these issues represent an insurmountable obstacle for *Argo*.

The excitement created by *Argo* is in part due to the fact that it represents an extremely cost-effective solution. The best estimates available at this time suggest that *Argo* will require US$10-12M per year, including all ancillary costs such as deployment, telemetry and data assembly. This gives an indicative cost of around US$100 per 2000 m temperature and salinity profile.

For oceanographers, *Argo* represents a near-revolution in ocean measurement. It is feasible, cost-efficient and worth doing, for both research and operational purposes. This paper outlines an initial strategy for exploiting this opportunity and identifies the most immediate issues to be addressed. As a result of the initial review process, and after further consideration by the *Argo* Science Team, more comprehensive and complete designs and implementation plans will be developed.

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Appendix: Argo Science Team Terms of Reference

GODAE and CLIVAR UOP jointly convened a Workshop in July 1998 to set the scientific and technical foundations for a global profiling project, now known as Argo. A Prospectus was drafted and the general specifications and implementation strategy agreed upon. The Workshop recommended the establishment of an Argo Science Team, jointly sponsored by GODAE and the CLIVAR UOP, to oversee the drafting of a detailed initial Implementation Plan and to provide continuing scientific and technical guidance.

GODAE and CLIVAR UOP have agreed to form an Argo Science Team with the following Terms of Reference:

i) Develop an Implementation Plan for a global network of profiling (temperature and salinity) floats, using the GODAE/UOP Prospectus and Workshop Report as representative of the CLIVAR and GODAE requirements.

(i) Provide scientific guidance to, and receive advice from, the Upper Ocean Panel of CLIVAR and the International GODAE Steering Team on the scientific and technical issues associated with the implementation of the profiling float contribution to the sustained (ocean) observing system of CLIVAR and the global ocean climate observing system of GODAE and GOOS/GCOS.

(ii) Develop an international consortium, to undertake the implementation and maintenance of the global network, and provide advice to the consortium as necessary.

(iii) Promote and evaluate observing system studies to guide the initial Argo sampling design and to guide the long-term development and evolution.

(iv) Provide advice and guidance technical innovations relevant to the float array.

(v) Liaise as appropriate with other groups associated with the (sustained) global ocean observing system, including the ship-of-opportunity program, the tropical atmosphere-ocean array, and remote sensing program such as Topex/Poseidon and Jason.

(vi) Provide regular reports on progress to the GODAE and CLIVAR International Project Offices.

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