

THE ROLE OF XBT SAMPLING IN THE OCEAN THERMAL NETWORK

Neville R. SMITH¹, D.E. HARRISON², Rick BAILEY³, Oscar ALVES⁴, Thierry DELCROIX⁵, Kimio HANA WA⁶, Bob KEELEY⁷, Gary MEYERS⁸, Bob MOLINARI⁹ and Dean ROEMMICH¹⁰

¹ BMRC, Box 1289K, Melbourne Vic. 3001, AUSTRALIA

² NOAA/PMEL, 7600 Sand Point Way, Seattle, WA 98115, USA

³ JAFOS, BMRC, Box 1289K, Melbourne Vic. 3001, AUSTRALIA

⁴ UKMO, London Rd, Bracknell RG12 2SY, UK

⁵ IRD, BP A5, 98848 Noumea, NEW CALEDONIA

⁶ Tohoku Univ., Aoba-ku, Sendai 980-8578, JAPAN

⁷ MEDS, 1202-200 Kent Street, Ottawa, Ontario K1A 0E6, CANADA

⁸ CSIRO Marine Research, Castray Esplanade, Hobart Tas. 3001, AUSTRALIA

⁹ NOAA/AOML, 4301 Rickenbacker Causeway, Miami, FL 33149, USA

¹⁰ Scripps Institution of Oceanography, La Jolla CA 92093-0230, USA

ABSTRACT - This paper evaluates the present role of the XBT program and proposes a strategy for the future under the assumption that there are other direct and indirect contributions to sampling the temperature and salinity of the ocean. Since the focus is on XBT sampling the paper restricts its scope to the upper ocean, mostly above 1000 m. The conclusions of the paper are based on a study and workshop that were convened specifically to look at the design of the ship-of-opportunity network and to look at options for its implementation in the future under the assumption that Argo happens. The paper also addresses issues related to data distribution and management. The primary conclusion is that the network of the future should place greatest emphasis on line sampling, at intermediate to high densities, and assume that a proposed profiling float array, Argo will largely take over the role formerly occupied by area (broadcast) sampling. It is argued that line sampling exclusively addresses several needs of the ocean observing system that cannot easily be addressed by other forms of sampling. Further it is argued that such a mode complements other in situ components such as moorings and floats as well as remotely sensed surface topography. A new network is outlined with a strategy for implementation that ensures continuity between existing and planned networks. We conclude the data management system that was established around the SOOP program requires substantial renovation if it is to adequately address the needs of the data gatherers and suppliers, and the data users (modellers, scientists, operational applications).

1 - BACKGROUND.

While we have been collecting thermal samples of the ocean for much of this century (Figure 1), it is only in the last quarter of the century that oceanography has been able to take advantage of cheaper, more cost effective expendable and autonomous instrumentation. Many of these advances are addressed in other

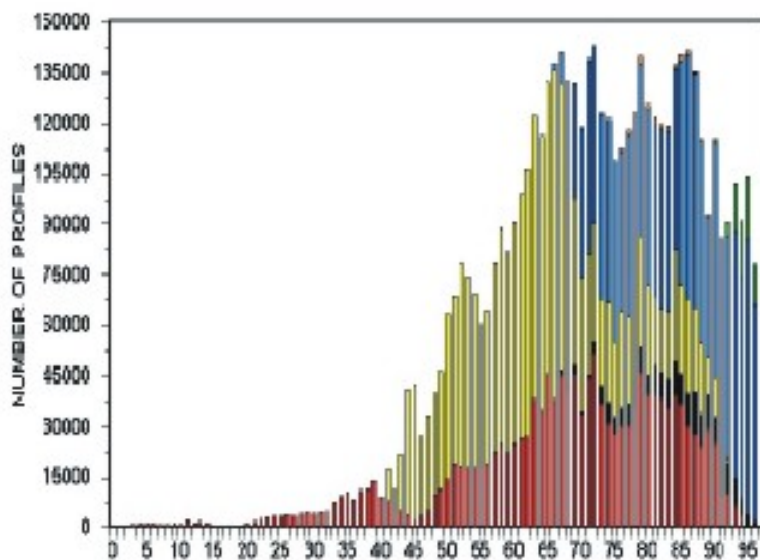


Figure 1. Profile count for the World Ocean Database 1998 (Levitus et al 1998). Bottle casts are in red/brown. CTD casts are shown in black. The yellow are mechanical bathythermographs while XBTs are shown as steel blue. TAO data are shown in green.

papers of this Conference. The eXpendable BathyThermograph (XBT) was introduced around 30 years ago and opened up the possibility of gathering inexpensive measurements from ships-of-opportunity and thereby avoiding the costly overheads associated with research vessels. Such a strategy has been employed for the collection of marine data since the middle of the last century and continues to be an important component of the World Weather Watch. The ship-of-opportunity program (SOOP) was initiated to develop this capability for upper ocean observations. The first significant networks were established in the North Pacific and North Atlantic Oceans and led to improved understanding of the upper ocean in those regions.

The major impetus for a more extensive network came from the Tropical Oceans-Global Atmosphere Experiment (TOGA) and the World Ocean Circulation Experiment (WOCE). The TOGA and WOCE programs used ships-of-opportunity to deploy XBTs along selected routes. The networks were first extended into the tropical oceans to capture variability associated with El Niño and later to other mid-to high-latitude regions, providing data for observing network design and for fundamental studies of ocean variability and predictability. The tropical network was critical for developing models of ENSO and continues to be an important contribution to the initialization of prediction models. SOOP thermal data also constitute a significant fraction of the recent global upper ocean thermal data base (Fig. 1) and so to a large extent represent our "knowledge" of the seasonal cycle and interannual variability.

The Tropical Atmosphere-Ocean array (TAO; McPhaden 1995; Hayes et al 1991) was an initiative of TOGA and presently constitutes the core of the (operational) ENSO observing system. Till this point it has been argued that TAO and SOOP are complementary and that any redundancy that does exist could not be removed without significant effort and loss of capability (see also Anderson et al, this Conference). While this may be true, it is timely for the ocean community to look at this issue afresh and re-articulate the justification for a major tropical ocean SOOP and, where uncertainty exists, encourage appropriate studies.

In the early 1990's the US and France launched the Topex/Poseidon altimeter. This instrument delivered, and continues to deliver, estimates of surface topography changes to an accuracy of around 2 cm (Mitchum

et al, this Conference). This capability, plus the development of skilful model and data assimilation systems, has changed the perceived role of SOOP data. With such information available it does not make sense to design and evaluate networks such as SOOP in isolation. Networks must be considered as a contribution to a larger, integrated in situ and remote system, with consequences for sampling and design.

There are now also firm plans for a global array of profiling floats (*Argo*; *Argo* ST 1998 and Roemmich et al, this Conference). In theory *Argo* will deliver an upper ocean profile (around 1500-2000m) of T and S every 10 days or so from around 3000 floats. This will revolutionize the upper ocean observing network.

The last concerted examination of the SOOP network was undertaken just prior to the establishment of the Climate Variability and Predictability Programme (CLIVAR) (TWXXPPC 1993). This paper and the associated workshop and study represent a logical progression from that point taking into account innovations over the last 6 years. For the purposes of this study, the rationale for the observing network is provided by OOSDP (1995) and the CLIVAR Implementation Plan (WCRP 1998), plus the action plan for ocean observing system for climate (IOC/WMO 1998) The Workshop also examined some issues associated with salinity. These are not pursued here (see Lagerloef and Delcroix, this Conference).

2 - A STUDY OF THE UPPER OCEAN THERMAL NETWORK

The GCOS/GOOS/WCRP Ocean Observations Panel for Climate (OOPC), CLIVAR Upper Ocean Panel (UOP) and the Ship-of-Opportunity Program of the IOC/WMO Integrated Global Ocean Services System (IGOSS SOOP) agreed to convene a study of the upper ocean network with the support of NOAA and the Bureau of Meteorology. The aims of the study were

- 1) To compile a consolidated account of the existing upper ocean thermal (UOT) data base, using whatever data bases that are available;
- 2) Produce consolidated "maps" of information level/content based on the dominant scales of climate signals;
- 3) Document the existing practices for assembling, quality control and distribution of upper ocean data;
- 4) Document to the extent possible the "value adding" of thermal data process chains, be they automated assimilation, quick-look/semi-automated quality control or higher-level scientific quality control and assembly.
- 5) Provide quantitative assessment of all SOOP lines including an assessment of relevance/impact against scientific objectives
- 6) Provide a renovated SOOP plan taking account of, as far as is practical
 - The existence (or potential) of other direct sampling networks (e.g., TAO, *Argo*);
 - The indirect information available from remote sensing, particular altimetry; and
 - The indirect information available from models, e.g. wind-forced equatorial.

The study and associated workshop report (*An Ocean Thermal Network Review, in preparation*) provide the substantial input for this paper. Some of the details will be provided in a separate paper (Bailey et al, this Conference). The plan here is to first discuss some of the scientific and historical background to the present SOOP network (Section 3), including the rationale for the three most prominent modes of sampling (i) low density broadcast (areal) mode, (ii) frequently-repeated lines, and (iii) high-density sampling. We will then extend this discussion by introducing the main scientific goals for the network (Section 4), most

of which are not exclusive to SOOP. They do however provide a suitable framework from which to develop a picture of why XBT sampling has utility. Sections 5 and 6 describe what the XBT program can and should contribute and introduce a new strategy for XBT sampling given certain assumptions about other elements of the system. Section 7 discusses various aspects of data assembly, management and processing and concludes that a major rethink of the approach might be warranted. Specific suggestions are put forward. Section 8 concludes the paper by recapitulating some of the major conclusions and suggests a prioritized timetable for the implementation of the recommendations. Some discussion of cost is also included.

3 - SCIENTIFIC BACKGROUND

In this section we outline the scientific rationale behind the sampling strategies that have been developed for the ship-of-opportunity network to this point in time. While we do emphasize the importance and, in some cases, the fundamental contributions from the SOOP network, there is also the implicit acknowledgment that the observational environment has changed and continues to change and that it is therefore timely to re-evaluate the deployment of SOOP resources. We also note that although we are here focussing the discussion around three modes of sampling, in practice the division between these modes is blurred. A fourth mode has provided much of the historical XBT data. This latter mode consists of data collected during basic research experiments and military applications. Typically, data are taken from

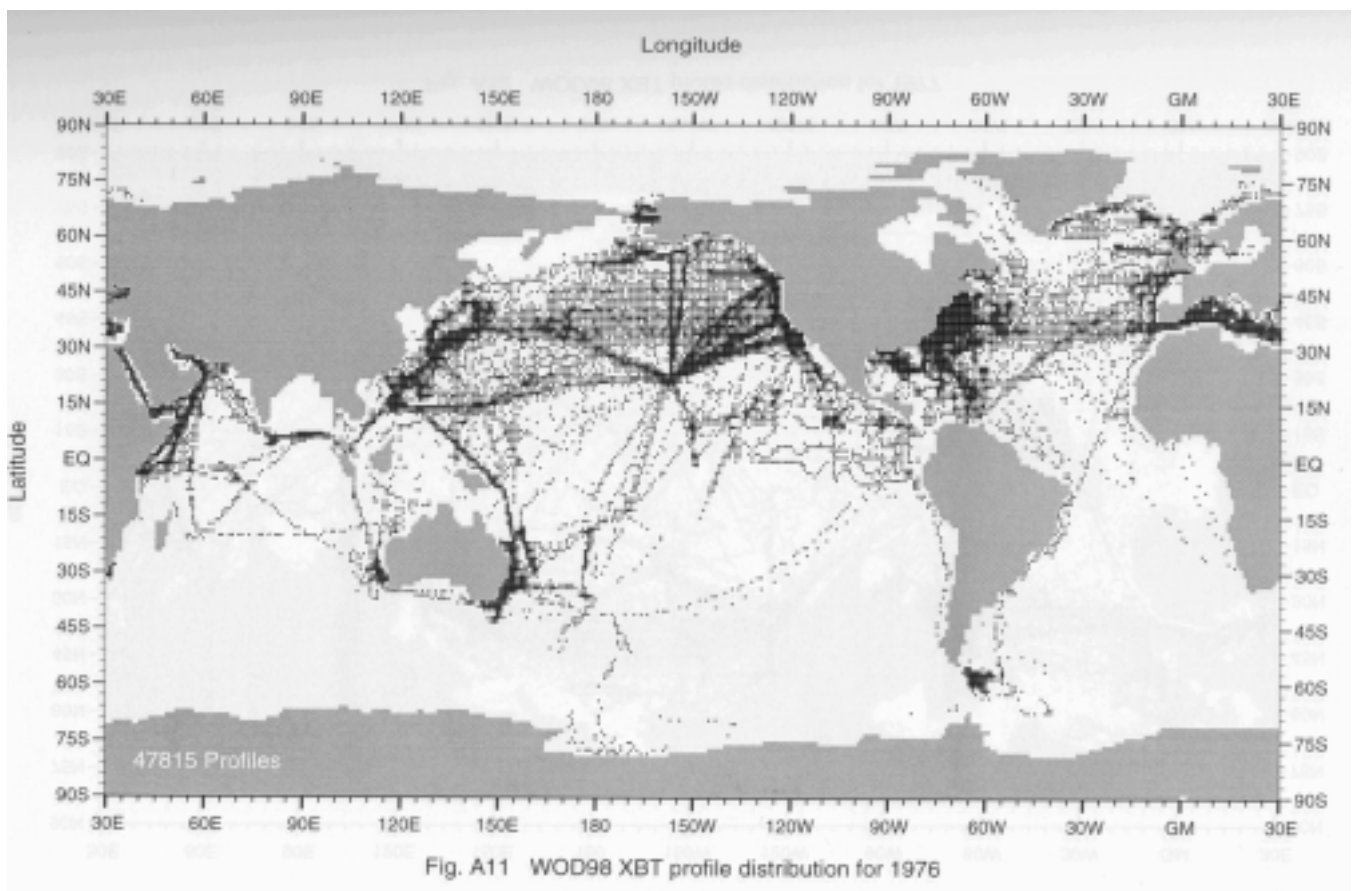


Figure 2. Distribution of XBT profiles for 1976 (from Levitus et al. 1998).

research vessels in limited areas but with intense sampling. Much of the early North Atlantic sampling in the Gulf Stream region is of this type. Figure 2 shows an example of the annual distribution of data during this period.

3.1 - Low resolution sampling

Low-resolution sampling (sometimes referred to as broadcast or areal sampling) was the dominant mode in the early days of the ship-of-opportunity network. The original rationale was that it targeted the large-scale, low-frequency modes of climate variability and made no attempt to resolve the energetic, mesoscale eddies that are prevalent in much of the ocean. The early studies used sampling rates that, within the resources available, would provide over-sampling of the relevant modes of variability. It was then possible, on the basis of simple estimation theory (e.g., Gandin 1963) to calculate the relevant scales of spatial variability. The results of such studies formed the basis of the network design adopted for TOGA. Molinari et al (1992) discuss several of these studies and note the variation in temporal and spatial scales.

The current low resolution network is comprised of data from 1) VOS XBT lines along which sampling ideally has been monthly and 4 drops per day (as established during WOCE and TOGA) and 2) basic research and operational experiments in which XBT's are dropped in grid-like patterns to study various oceanographic phenomena (the early high-resolution sampling noted above). The low-resolution lines are maintained through an international consortium with oversight by the SOOP Implementation Panel and data are frequently available in real-time for operational climate forecasts and analyses. The experimental data are available in a delayed mode when (ideally, but not always in reality) investigators provide their data to a national data bank.

The present SOOP network is shown in Figure 3. It is evident that while the coverage is extensive, it is not global and that there are large gaps in the network. The availability of data is adequate for studies of low frequency variability (Festa and Molinari, 1992; TWXXPPC 1993). Extensive use of such data has been made in the tropical Pacific (e.g., Meyers et al 1991; TWXXPPC 1993; Taft and Kessler 1991) and in studies of global modes of variability (e.g., White 1995). There have also been extensive studies of decadal variability in the North Pacific (Hanawa and Suga 1995). Hanawa and Yoritaka (1999) and Yasuda and Hanawa (1999) argue that XBT data are particularly useful for North Pacific Subtropical Mode Water studies. The scales of variability of mode water and the distribution and circulation of associated water properties can be readily captured by broadscale sampling. The unique niche of the low resolution mode among global ocean observations is in the 30 plus years worth of data along some lines and regionally in the North Atlantic and North Pacific.

Low resolution data are also used routinely in ocean analysis and climate model initialisation. For El Niño prediction, XBT data complement that from TAO (Smith and Meyers 1996; Anderson et al this Conference) though it is difficult to precisely quantify their contribution in the presence of altimetry and good models. XBT data also are a staple input for several global ocean analysis systems (e.g., Clancy et al 1997). In the latter cases, there are tight constraints on timeliness. The use of XBT data to measure the seasonal and interannual fluctuations in the upper layer heat storage and to serve as constraints on estimates of air-sea fluxes in areas where the balance is primarily one-dimensional constitutes one of the (formerly) unique roles of SOOP. XBT data also play a key role in the determination of regional patterns of upper layer temperature structure in well sampled areas. Figure 4 shows such an analysis of decadal temperature changes in the North Atlantic. There are also many other examples where low-resolution data play a significant role (e.g., Deser et al 1999).

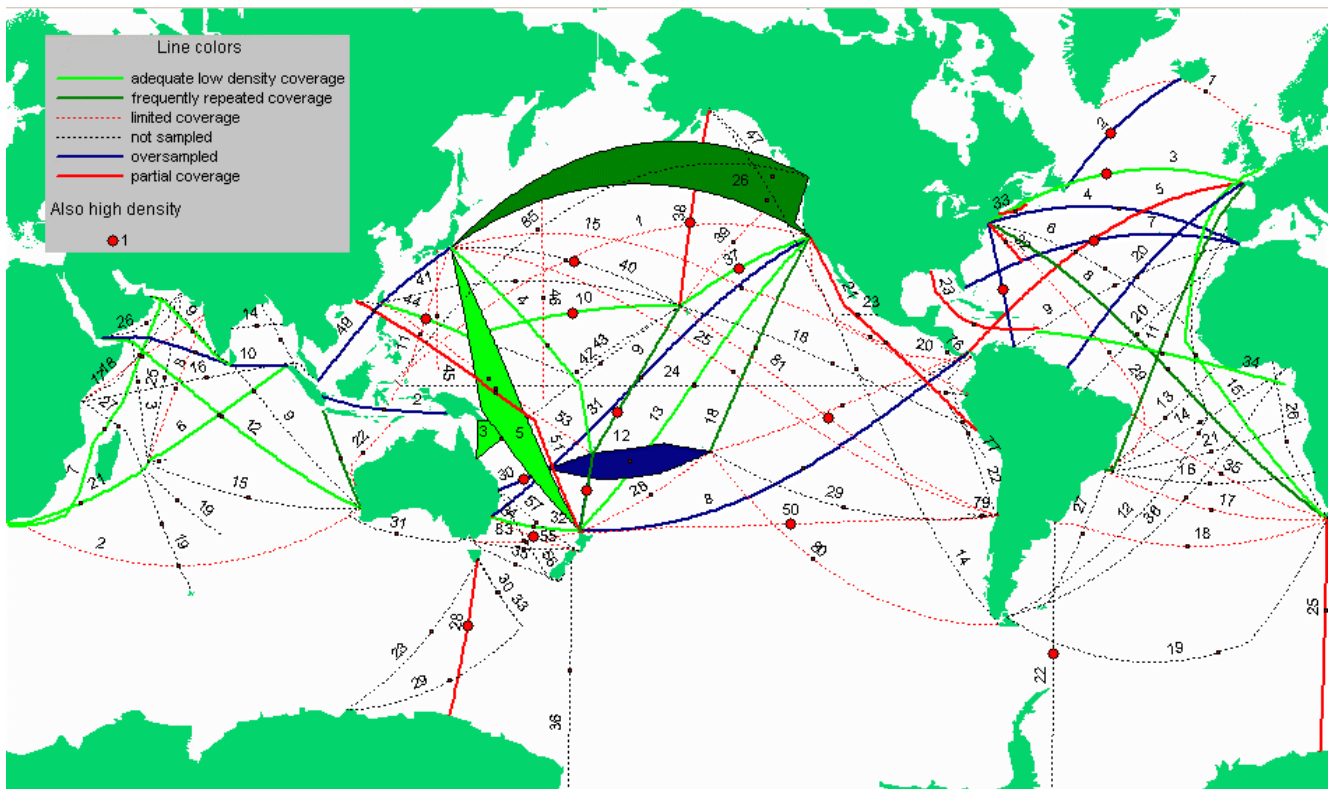
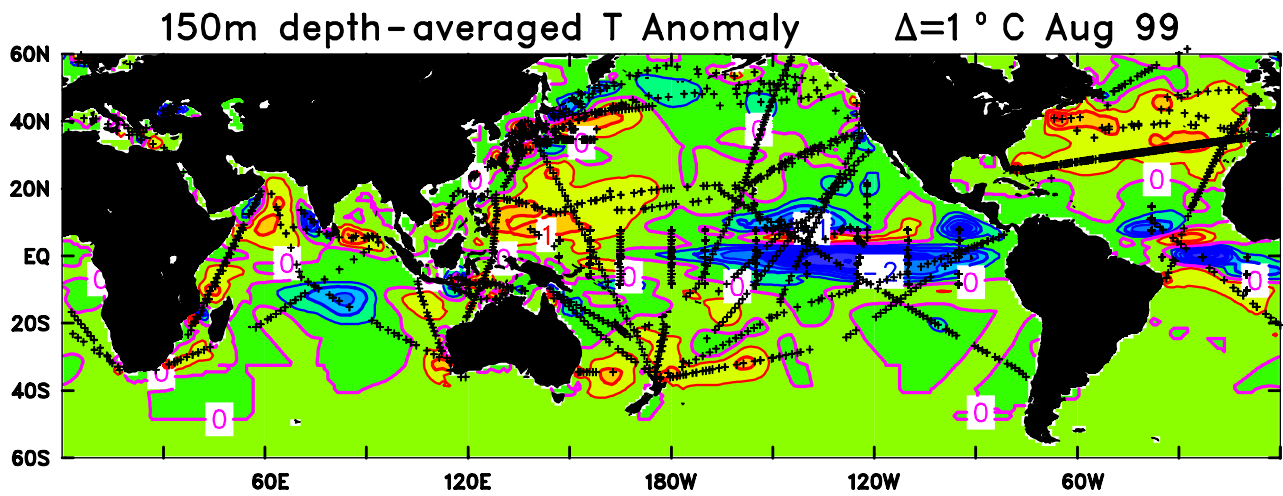
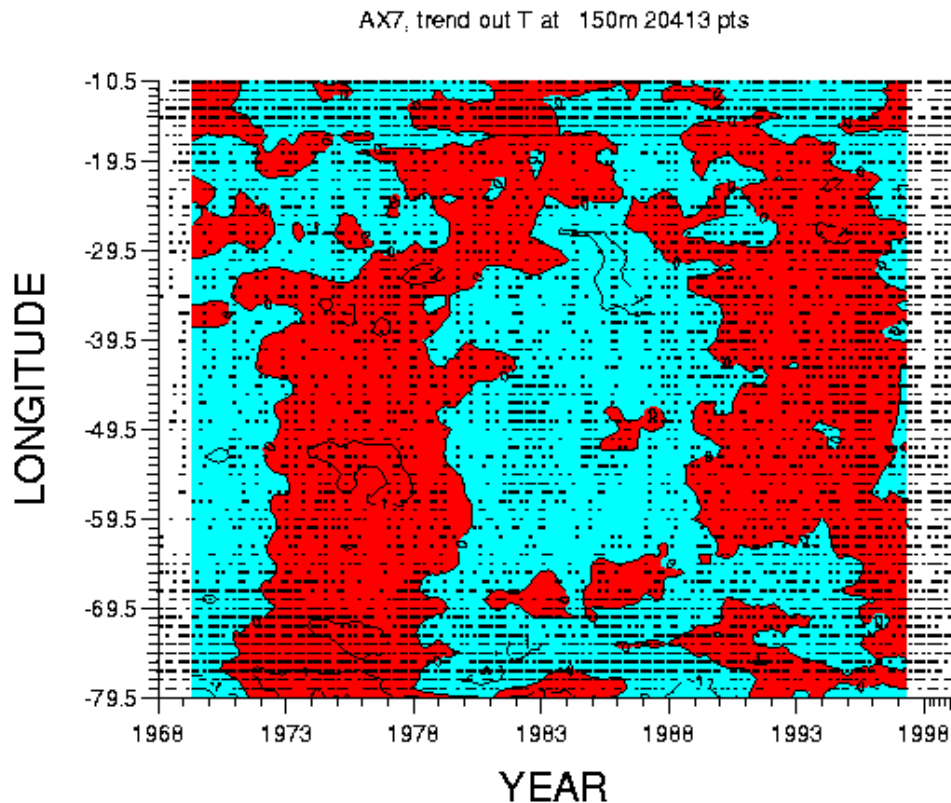


Figure 3. (Top) Typical data distribution (August 1999) for the present network comprising SOOP, TAO and some profiling floats. The majority of the SOOP lines are maintained in low-density mode. (Bottom) The SOOP network design show low-density line of adequate coverage (light green), frequently-repeated lines (dark green), limited coverage (dashed red), not sampled (dashed blue), oversampled (dark solid blue) and partial coverage (solid red). Lines that are also high density (see Fig. 5) are marked with red dots.

Lines that cross intense boundary currents and have been occupied continuously for more than 10 years provide a unique source of information on the variability at time scales greater than interannual and in some cases decadal. It is unlikely that other data can provide similar information because of the high advective speeds in these currents. In some cases the sampling rate exceeds that normally associated with broadcast mode. Furthermore, lines that have been occupied for more than 20 years constitute an important component of our historical thermal data archive.



3.2 - Frequently repeated sampling

3.2.1 - *What are frequently repeated lines?*

Frequently repeated XBT (FRX) lines are mostly located in tropical regions to monitor strong seasonal to inter-annual thermal variability in the presence of intra-seasonal oscillations and other small scale geophysical noise. The lines typically run almost north/south, and cross the equator or intersect the low latitude eastern boundary. They are intended to capture the large scale thermal response to changes in equatorial and extra-equatorial winds. Sampling is ideally on an exactly repeating track to allow separation of temporal and spatial variability, although some spread is possible. The lines are (ideally) covered 18 times per year with an XBT drop every 100 to 150 km. An extra XBT is dropped at the 200m depth contour when crossed if possible. Volunteer observers on merchant ships do the sampling.

FRX sampling tries to draw a balance between undersampling and greatly increasing the risk of aliasing, and more expensive high-density sampling. Its niche is in regions where temporal variability is strong (and resolvable with order 20 day sampling) and spatial variability is not dominated by scales at the Rossby radius. The oldest FRX lines have been monitored for 20 years, allowing accurate documentation of seasonal and inter-annual variations of thermal structure and very accurate documentation of differences between decades.

3.2.2 - Where are FRX lines most valuable?

Lines in the FRX network were selected to satisfy the following general criteria:

- Meridional lines crossing the equator or intersecting the low latitude eastern boundary in the tropical western, central and eastern parts of the Pacific, Atlantic and Indian Oceans (Fig. 5).

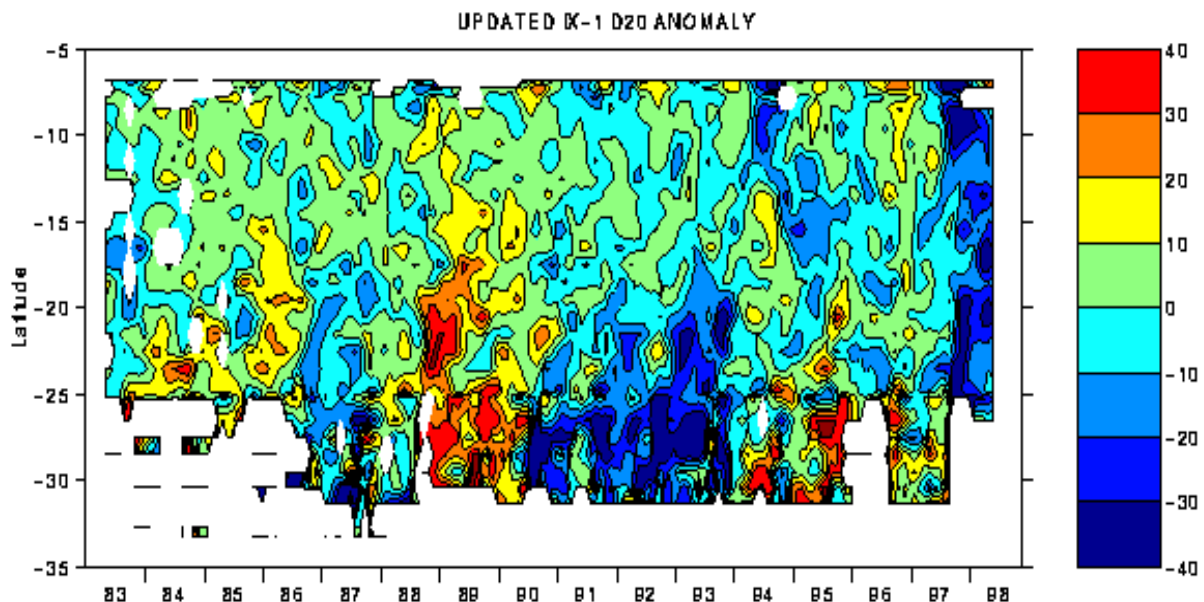


Figure 5. The evolution of the anomaly in the depth of the 20°C isotherm along line IX1. Note the significant events in 1988, 1991-93 and 1998. [G. Meyers, pers. Comm.]

- Lines across important regional features of the climate system, such as Indonesian throughflow, North Equatorial Countercurrent (NECC) in response to Intertropical Convergence Zone (ITCZ), Western Pacific Heat Pool, Somalia upwelling zone, etc.
- Isolated lines in the poorly sampled parts of the tropical oceans, where widely dispersed low density sampling is not possible due to ship-routing patterns.

The future of all modes of XBT sampling should take into account the availability of global altimetric data, offering the potential for synthetic XBT's in regions where the T/S relationship is not too variable, as well as the planned development of global thermal measurements by the *Argo* Program. With only a few

exceptions, the FRX lines have not been managed with enough tenacity to ensure the sampling occurs on a narrow, repeating track-line. This is relatively easy for XBT operators to fix, but it requires extra time and attention to detail to select and change ships when required.

Whether or not FRX lines have any particular value for initialisation of seasonal climate predictions and/or ocean estimation using a dynamical model has not been clearly demonstrated. In principal, models should be able to exploit the long zonal scales to export information well beyond the line of measurement. In practice, it seems, model and/or wind errors contrive to diminish this potential value.

3.3 - High-density XBT (HDX) sampling

3.3.1 - What are high resolution lines?

High resolution XBT (HRX) lines are those whose sampling criteria require boundary-to-boundary profiling, with closely spaced XBTs to resolve the spatial structure of mesoscale eddies, fronts and boundary currents. The present set of regularly sampled HRX lines are shown in Figure 6, with probe spacing (typically 10-50 km) displayed from a single realization along each transect. Time-series of HRX lines are as long as 13 years in the case of PX6 (Auckland-Suva). The repetition frequency is about four times per year. In most cases, a technician or scientist on board the ship makes measurements.

HIGH RESOLUTION XBT/XCTD NETWORK

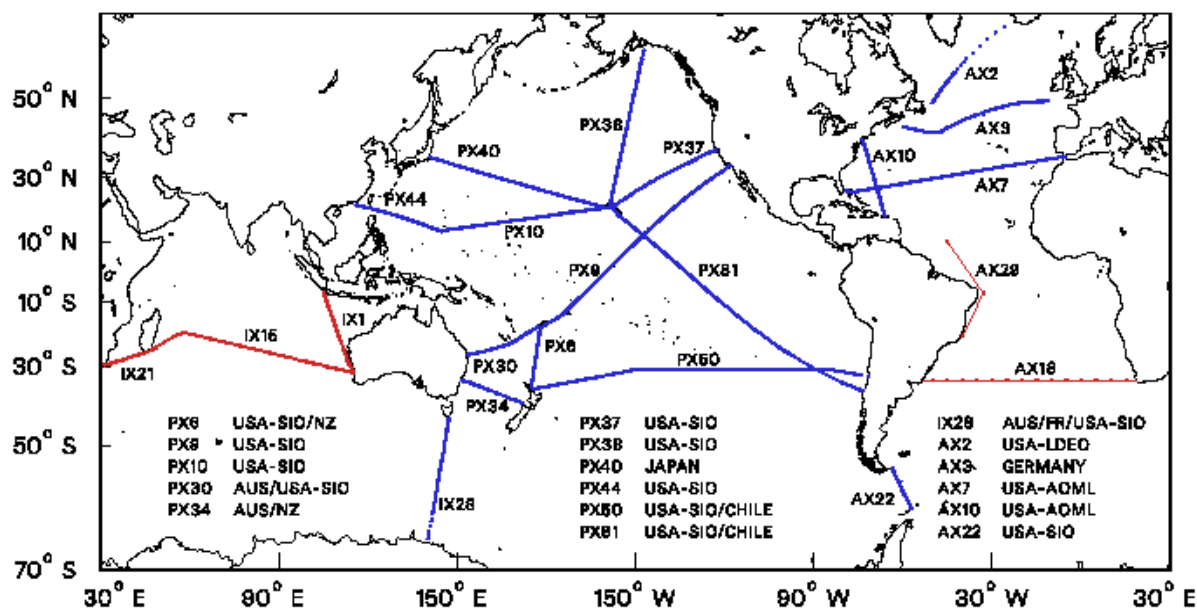


Figure 6. Map of the HRX lines. Presently sampled routes are shown in blue, with symbols at station locations from a single cruise. High-priority additions (see Section 6) are shown in red.

The unique niche of the HRX mode among global ocean observations is in spanning spatial scales from that of eddies and boundary currents to basin-width, and time scales from seasonal to (potentially) decadal. The closest analog to HRX sampling, but usually in regional scale observations, is repeat hydrography.

HRX sampling is substantially more labor-intensive than broad-scale or high frequency lines. It returns higher quality datasets through use of (i) a stern-mounted automatic launcher (ii) redrops of questionable profiles (iii) horizontally coherent sampling. The characteristics and objectives of HRX lines dictate careful selection of a limited set of routes for this sampling mode.

3.3.2 - Scientific objectives addressed by HRX sampling.

HRX transects are an important means for addressing the following objectives.

- Measure the interannual fluctuations in the transport of mass, heat, and freshwater across ocean-spanning transects (e.g. at tropical/ subtropical boundaries, Figure 7) or through the perimeter of large ocean areas (e.g. Tasman Box PX6/30/34, Western Atlantic AX7/10 etc.);

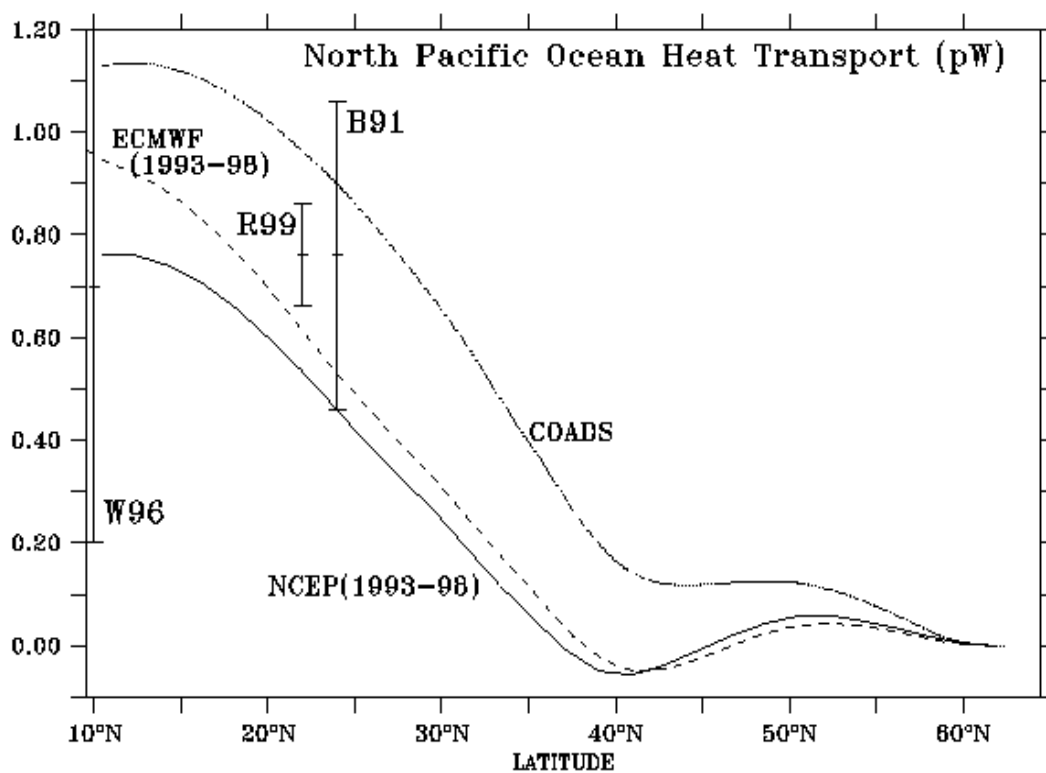


Figure 7. Meridional heat transport (pW) in the North Pacific Ocean. B91 (Bryden et al 1991) and W96 (Wijffels et al, 1996) are from the one-time hydrographic transects. R99 (Roemmich et al 1999) is based on geostrophic and Ekman transport calculations from 25 HRX transects along P37/10/44 (average latitude 22°N) from November 1992 to January 1999, with simultaneous wind measurements. The other estimates are from climatological data or operational products as indicated. Accurate estimates of ocean heat transport can be used to test or constrain modeled air-sea fluxes.

- Characterize the structure of baroclinic eddies (Fig 8) and estimate their significance in the transports of heat and water masses;
- Determine the spatial statistics of variability of the temperature and geostrophic velocity fields (Fig 9);
- Identify persistent or permanent small-scale features;

- Determine the scale-dependent correlation of sub-surface temperature and dynamic height with altimetric height (Fig 9). What are the minimal requirements for in situ data?

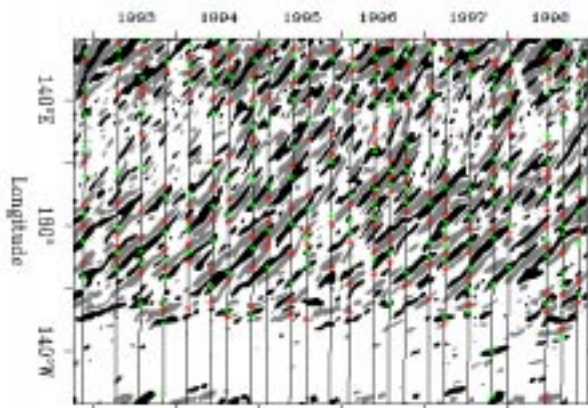


Figure 8. Complementary information in TOPEX altimetry and HRX dynamic height. Eddy locations are shown from the T/P altimetry and HRX data along P37/10/44 as a function of longitude and time. Warm (cold) eddies with sea surface height maxima (minima) are shown as red (green) symbols for XBT data and gray (black) for T/P data. Note how individual eddies can be identified and tracked for a year or longer, propagating westward at 10 cm/s. (From Roemmich and Gilson, 1999.)

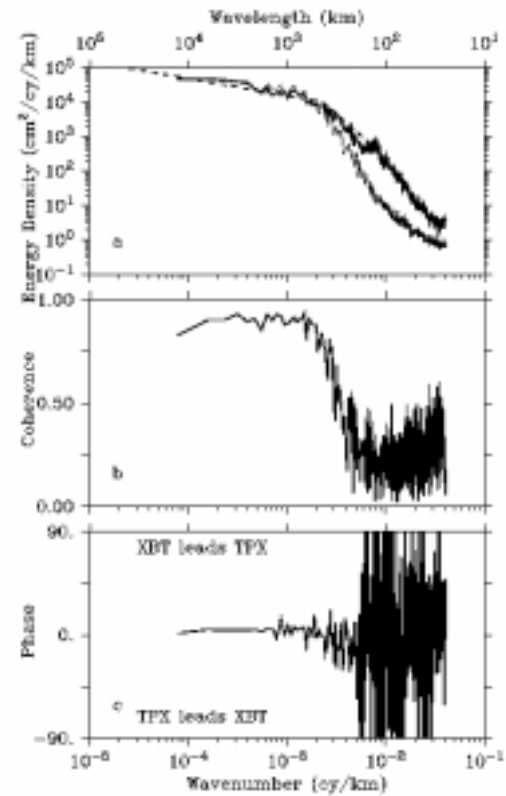


Figure 9. Horizontal wavenumber spectra and coherence of dynamic height (solid) and altimetric height, along PX37/10/44. Note the high coherence (> 0.9) at low wavenumbers ($\lambda > 500$ km). (From Gilson et al., 1999)

- Facilitate additional measurements from a small set of highly instrumented Volunteer Observing Ship (VOS) platforms (XCTD, SSS, improved SST and meteorological observations, float deployment etc.); and
- Determine the long-term mean, annual cycle and interannual fluctuations of temperature and large-scale geostrophic velocity and circulation in the top 800 m of the ocean (Fig 10).

3.3.3 - Where are HRX lines most valuable?

Lines in the HRX network were selected to satisfy several general criteria subject to specific shipping availability and basin geometries. These are:

- Zonal ocean-spanning transects across the subtropical gyres, where meridional ocean heat transport is large, and at other special locations.
- Meridional lines (with maximum extent in latitude) crossing the equator in the western, central and eastern Pacific
- Choke point transects.

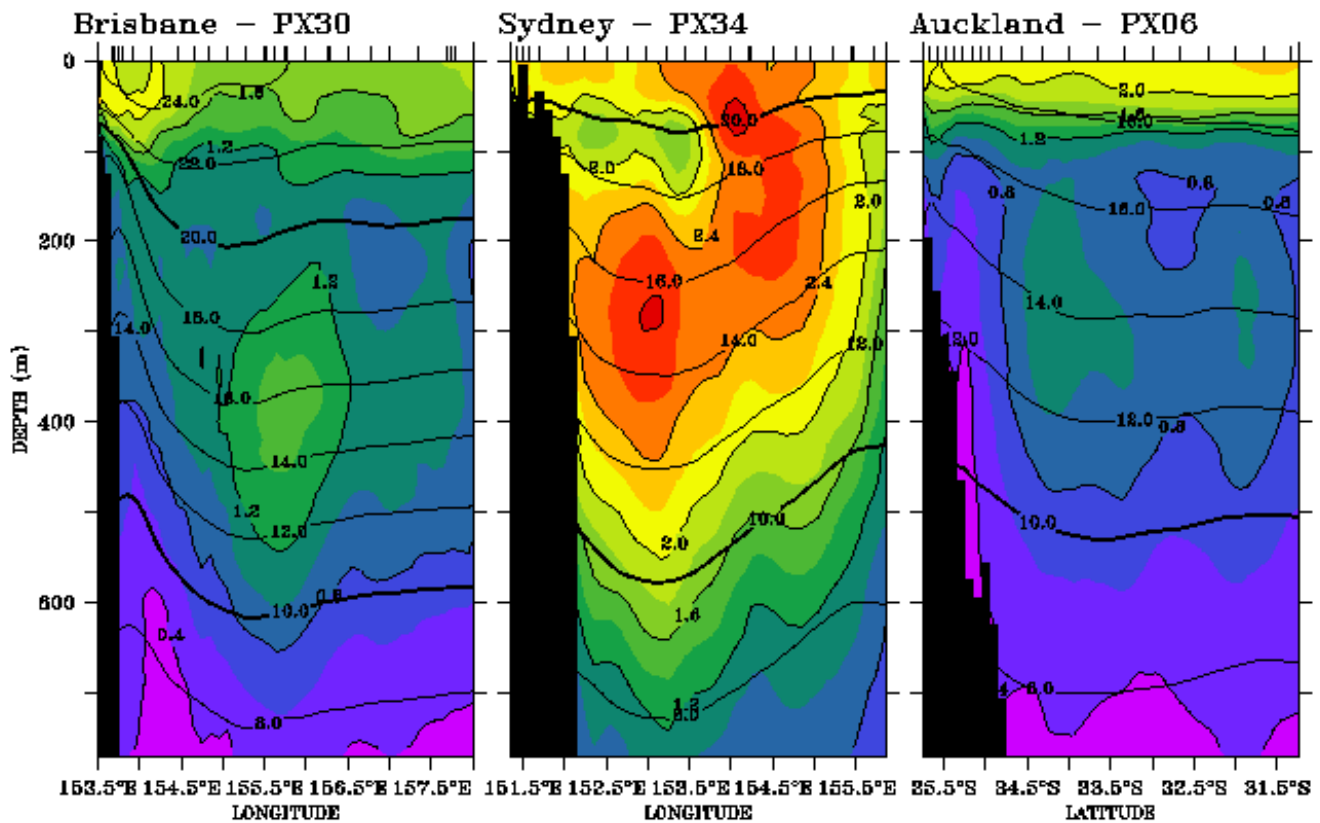


Figure 10. Long-term sampling of western boundary currents in the southwestern Pacific. The East Australian Current (EAC) is sampled by 2 transects, PX30 off Brisbane, and PX34 off Sydney, each with about 30 transects from 1991 to the present. The EAC separates from the coast north of Sydney, but overshoots and then re-curves northwestward across PX34. Part of the current reattaches to the northern New Zealand coast as the Auckland Current, sampled by over 50 transects since 1986 along PX06. The figure shows the mean and standard deviation of temperature for the three western boundary current crossings. Note the offshore maximum in variability at all three locations. Tick marks at the top are single-cruise XBT station positions. [Roemmich, personal comm. and Sprintall et al 1995]

- Selected "boxes" in eastern or western boundaries.

Given these criteria, the most significant shortcomings of the present HRX network (Fig. 6) are the lack of:

- Zonal transects across the subtropical S. Indian (where one was discontinued in 1995) and S. Atlantic.
- A meridional line crossing the western equatorial Pacific
- Choke point transects from S. Africa to Antarctica and across the Indonesian throughflow (presently a frequently repeated line; Rintoul et al 1997).

Experience shows that the most valuable HRX lines are those that are maintained along exactly repeating routes for periods of 5 years or longer. There is little reason to initiate HRX lines if they cannot be maintained, and higher priority is attached to maintaining long time-series lines than to initiating new ones.

There is a very complementary relationship between HRX lines and frequently repeated lines. The latter provide important context consisting of long-term climatologies and improved temporal resolution that

balance the high spatial resolution of the HRX mode. Because of this, existing frequently repeated lines are the best candidates for new HRX sampling.

4 - THE OPERATIONAL AND SCIENTIFIC FRAMEWORK FOR THE FUTURE

For the immediate future, it is the practical applications associated with the Global Ocean Observing System and the scientific objectives of CLIVAR that provide the main rationale for maintaining an upper ocean thermal network. This paper does not address the overall design of this observing system but instead focuses on those elements that are impacted by the SOOP. However it is not possible to do this without first considering the broad objectives for the upper ocean thermal network, be they practical or scientific. We do this by re-expressing the relevant scientific objectives of the CLIVAR Implementation Plan (WCRP 1998) and of GOOS (OOSDP 1995; IOC/WMO 1998) as a small set of goals. There is a level of arbitrariness in this choice but this cannot be avoided. We argue that, in order to re-design the SOOP network and assign priorities, we must have a clear set of reasons out front; Why do we want an upper ocean network? These reasons are in general not exclusive to SOOP and do not even encompass all the reasons for using XBTs but there is little to be gained by making them greatly more complex. Rather, we will use these objectives as a means for ordering the discussion and the evaluation of the individual contributions (lines).

The Study (see Bailey et al, this Conference) use the following scientific objectives as the basis for its evaluation of the SOOP contributions in the past. As we will indicate in subsequent sections, the future system is likely to be targetted at more specific aspects.

4.1 - The scientific objectives

a) Seasonal-to-interannual prediction (ENSO)

- There are many centres that now run routine / operational ENSO prediction systems (see Anderson et al, this Conference). There are many more that have experimental systems. The dependence on ocean data varies but there is clear evidence from both hindcasts (e.g. Ji et al 1998; Kleeman et al 1995) and applications in practice (WCRP 1999) that subsurface data are important.

b) Understanding tropical ocean variability, predictability

- In parallel with practical applications are research efforts attempting to understand tropical ocean variability and the predictability of the coupled climate system. Many of these issues are addressed in the CLIVAR Implementation Plan and are addressed in other papers from this Conference (Garzoli et al; Meyers et al; McPhaden et al).

c) Mid- and high-latitude ocean variability (intra-seasonal to interannual)

There is significant ocean variability in the extra-tropics and higher-latitudes on scales ranging from weeks (boundary current meanders, eddies) to seasons and years (e.g., the ACW). What strategy should be employed for the UOT network? For the SOOP network? How do we exploit complementarity between altimetry and the UOT network? What role should SOOP play in an *Argo* world?

d) Global and regional heat storage

On interannual and longer time scales there are significant regional and global variations in heat storage and water mass formation with important implications for the climate system. Several papers at this Conference discuss longer time scale modes and the implications that might be drawn in terms of required observations. The challenge is to design a UOT network, with contributions from SOOP, *Argo* and other in situ and remote systems, that can give useful estimates of the rate of storage and release. Global coverage is essential but temporal and spatial resolution requirements might be less demanding. Issues of quality, however, are likely to be more demanding.

e) Heat and mass transport / circulation

Geostrophic transport of heat (and freshwater) is thought to be a key element of the climate system at interannual and longer time scales. The western and eastern boundary currents are known to be important and, as discussed in Section 3.3 and shown in Figs 7 and 8, transport by baroclinic eddies is also likely to be critical. What is the role of the SOOP network in delineating time and space scales of variability and in monitoring transports? As was suggested in Section 3, it is likely SOOP can play a singularly important role in this area.

f) Ocean state estimation / short-range ocean forecasting

The Global Ocean Data Assimilation Experiment (GODAE; see Le Traon et al, this Conference)) is one manifestation of renewed interest in ocean state estimation, but with the time scales of interest now ranging from a few days to annual and longer. To a large extent the goals introduced above cover the longer time scale aspects though, it should be noted, for at least some areas models will play a less prominent role than envisaged for GODAE. Many centres already operate routine ocean analysis and short-range ocean prediction systems. The utility of ocean data is beyond question, the remaining question here being whether the broad range of practical applications envisaged for GODAE influence the preferred design for the SOOP network. Certainly the need for regular ocean circulation estimates and short-range ocean prediction places a premium on rapid data delivery. On these time scales, it is the constraint of internal ocean variability that is important and it is hard to see SOOP being at the forefront.

g) Climatologies and climate change

Knowledge of the mean state of the ocean, including the seasonal cycle, is fundamental to most of the objectives introduced above. We cannot escape the fact that we have a short record relative to the time scales of several of the dominant modes of ocean variability. However we have a responsibility to ensure future generations are better placed than we are today. This means we should identify weaknesses/gaps in our knowledge of the mean state of the ocean (i.e., climatologies and their first moments), and pay attention to quality and data assembly in order to get data sets useful for monitoring climate change.

4.2 - The quantitative assessment

Just as there are many different ways of composing the goals, there are also many different ways of assessing the contributions against these goals. Bailey et al (this Conference) list the criteria that were used as the basis for evaluating contributions, line-by-line. The Workshop Report (to be published) gives a detailed assessment of the existing XBT database against these criteria for each of the objectives listed above. Largely independent of the specific goals, ratings were assigned for each line, with an explicit

recognition that such assessments were subjective and liable to be uncertain. However they provided a powerful method for quantifying the historical records. Each criterion was then assigned a weighting under a particular goal with the weighted sum for each line giving a measure of the importance of a line. Refer to Bailey et al (this Conference) for some further details.

5 - WHAT CAN THE SOOP XBTS CONTRIBUTE?

5.1 - Some assumptions

At this point we need to be more explicit with regard to some of the assumptions we must make. It is not possible to look forward for the SOOP network without some such working assumptions.

a) Tropical moorings

We will assume that an array similar to the present Tropical Atmosphere-Ocean array (TAO) is sustained in the equatorial Pacific (McPhaden et al, this Conference); that an array derived from PIRATA will be maintained in the tropical Atlantic (Garzoli et al, this Conference); and that some limited deployment of moorings in the Indian Ocean will occur on an experimental basis (Meyers et al, this Conference).

b) Global float array

We will assume an array of profiling floats (*Argo*) is sustained at coarse resolution (250-300 km) giving around 3000 profiles every 10-14 days (Roemmich et al, this Conference). These profiles will be to mid-depth (2000 m) and will be mostly T and S.

c) Altimetry

Assume a continuing altimetry program with both high-precision, low-resolution sampling (i.e., T/P and Jason series) and low-precision, high-resolution sampling (e.g., ERS) (Mitchum et al, this Conference).

d) Time-series stations

Assume that a limited set of time-series stations is established and maintained.

e) Acoustic thermometry

Assume that emerging technologies such as acoustic thermometry are deployed, at least regionally.

There is no certainty with any of these assumptions but it is sensible to acknowledge arrangements that are likely. These assumptions are not intended to exclude SOOP participation in particular areas if it is concluded that SOOP can provide a cost- and science-effective solution. In most cases however it is the complementarity which will be emphasised.

5.2 - The SOOP contributions

Here we wish to discuss the specific role of XBTs and state just what the SOOP can do. The order of the goals is modified a little to allow a somewhat better ordered introduction of the different proposed contributions.

5.2.1 - ENSO forecasting

As is noted by Anderson et al (this Conference), the TAO array remains the key contribution to initialization of practical ENSO forecasts models, both for its contributions to determining the surface wind and for its sampling of the subsurface equatorial ocean thermal field. These data lie at the heart of the initial conditions used by coupled forecast models. The fact that the equatorial ocean adjusts rapidly, with elongated zonal scales (order 1500 km) and narrow meridional scales (order 200 km) means that the TAO design is well-suited to this problem.

Given the sampling from TAO, one then might ask what role the SOOP could play. Smith and Meyers (1996) argued that the extra-equatorial data from SOOP came into play at longer lead times where the important information is being fashioned by the more slowly moving Rossby waves and conditions beyond the TAO array. Intuitively this seems reasonable. However in the presence of altimetry and *Argo* the importance of this contribution is negated, at least in the low- to intermediate density mode. The one aspect that is not adequately sampled is the meridional structure, particularly in the central-to-eastern Pacific. The importance one might attach to this has grown in recent times with several studies suggesting important links from the extra-tropics into the equatorial region via the sub-tropical meridional cell. However there is no evidence at this point that such data would have a positive impact on forecast models.

One should look forward with the expectation that models will improve and that the systems will likely to be sensitive to detail that is ignored today. At one extreme lie the intraseasonal effects and the hypothesis that predictability is intimately related to westerly wind bursts. At the other extreme is the hypothesis equatorial-extratropical exchanges introduce decadal modulations of ENSO, perhaps similar to the early 1990's. The former hypothesis draws down the temporal resolution, a demand that can probably be met by TAO. The latter requires systematic transects from the tropics into the extra-tropics and resolution of the meridional cells.

At the moment there is no firm evidence that ocean temperature data outside the tropical Pacific is other than of secondary importance. This however may simply be a reflection of the inadequacy of the models and the way they are initialized. Meyers et al (this issue) certainly put forward a persuasive case for Indian Ocean data, both XBTs and moorings. We conclude then that, in the presence of *Argo* and altimetry, there is no longer a strong case for low density SOOP sampling for ENSO forecasting. However sampling with frequent transects and intermediate spatial density appears justified along some north-south lines running through the central and eastern Pacific and in the Indian Ocean. Such data sets are not at the highest level of priority for this goal but would form a useful, complementary data set.

5.2.2 - Tropical ocean variability and predictability

One view of this goal is that it is the research extension of the practical focus in the first goal. Yet as Garzoli et al (this Conference) and Meyers et al (this Conference) show, there is much tropical ocean variability beyond the Pacific that has interest in its own right and that might in the future lead to practical applications. Even in the tropical Pacific, there are modes of variability such as tropical instability waves and adjustments due to westerly wind bursts that are for the moment not attributed high importance for model initialization.

We have already noted the importance of extra-tropical links, perhaps via the sub-tropical cells, and are thus giving strong support to a selection of intermediate-to-high density meridional transects with a repeat of around 20 days. Because of the sharp meridional gradients it is preferable that the sampling be at what

we term "eddy detection" scales; that is around 75 km compared with 20-25 km of high density sampling. The central and eastern Pacific are the preferred locations.

In the tropical Atlantic and Indian Oceans a similar set of transects is favoured. In the absence of mature mooring arrays such sampling takes on increased importance. We take the posture that such data, collected regularly, could be extremely effective at initializing the slower modes of adjustment and, with the aid of a good model and good winds, also the faster adjusting (Kelvin) modes. The model is used to fill out some of the spatial gaps and the wind, perhaps combined with altimetry, helps interpolate between transects. Frequently repeated sampling has proven extremely effective in the eastern Indian Ocean (e.g., Fig. 5) and there is every likelihood this will remain so in the future. One notes that at 120-150 km sampling density and a repeat of 20 days, the space-time sampling along these lines would be similar to *Argo*.

5.2.3 - Global and regional heat storage

To first order the sampling requirements are those of the low-density mode. That is, broad coverage is needed to map the gyre- to basin-scale changes in heat storage and that, because of the characteristic large-scale and low-frequency, the sampling density need only be modest in both space and time. Yasuda and Hanawa (1999), Deser et al (1999), Levitus et al (1994) and Molinari et al (1997) provide some examples of how such data have been exploited. The issue to be addressed here is: What is the role of XBT sampling given the presence of *Argo* and altimetry? While there is some need to ensure gaps are not opened up in key areas, the sampling of *Argo* seems more than capable of resolving the signals formerly addressed by LDX with the possible exception of areas where the circulation may prevent an even sampling by *Argo* (e.g., at some high-latitude locations). *Argo* will be global, will go deeper, will have salinity, and will have a nominal sampling density several times that of low density.

Because *Argo* will be phased in, the phasing out of areal sampling by SOOP should be done in such a way as to maximise global coverage and encourage at least some over-lapping period for cross-calibration.

5.2.4 - Heat and mass transport

As has been noted in Section 3.3, it is in this area that XBT sampling retains a unique role, a role that is unlikely to be usurped by any of the other proposed or speculated strategies. This arises from the fact that calculations of heat and mass transport, say across a mid-latitude gyre, require fine spatial sampling in order to avoid aliasing of eddy and other fine horizontal variability into the signal. The requirements are severe: XBT drops need to be every 20-25 km and the transects have to be from boundary-to-boundary. They should be repeated around every 3 months. Any gap in the transect, or weakening of the sampling rate, can introduce uncertainties of the same order as the signal being sought. It is also important the transects follow lines; that is, any cross-track spreading can compromise the utility of a line.

The conclusion then is that high-density sampling for heat and mass transport calculations remains an important, unique application of the SOOP. It should be noted that supporting altimetric data and, wherever possible, surface marine data, are extremely important. The altimetric data provide an immediate spatial context for transects as well as a direct estimate of dynamic height changes which can be calibrated against occasional XCTD profiles. The marine data permit a direct estimate of the wind-forced surface drift and thus some estimate of the contribution of the surface Ekman drift to meridional heat transport.

5.2.5 - Mid- to high-latitude variability.

There are many different aspects to this goal.

First in regions of boundary currents (e.g., the Kuroshio or Gulf Stream) or strong directional flow (e.g., the Antarctic Circumpolar Current; White and Peterson, 1996) XBT transects help resolve temporal variability and variations orthogonal to the flow. Figure 10 shows the variability measured in transects through the East Australian Current. Similar studies have been undertaken in the North Atlantic using AX7 and AX10. Knowledge of this variability and its impact on mean transports is clearly important. For the Southern Ocean such data clearly have high general significance (see Rintoul et al, this Conference) and high-density transects warrant sustained support. The boundary current transects provide information on variability that is not readily obtainable from other systems such as *Argo*. We therefore attach high priority to these lines.

The second important aspect is the characterization of baroclinic eddies and quantification of their significance in the transport of heat and water masses. There remain many unanswered questions about the way heat is transported from the tropics to high latitudes and about the way different water masses are circulated through the ocean. Clearly one set of information that is needed is measures of baroclinic eddies, at a resolution that avoids aliasing, with sufficient repetition and length of record to build a stable statistical picture of the interaction. Clearly, high-density lines are one of the few methods that are amenable to this issue. One might argue that this has the character of a process study rather than a sustained contribution, and so one would not wish to support transects/lines purely on the basis of this contribution. However, in the process of gathering data for measurements of heat transport, these statistics are readily derived, so it is useful to explicitly recognize this additional purpose.

Third there is the need to identify and characterize persistent or permanent small-scale features (eg, the Great Whirl in the western Indian Ocean). These features may well have some long-term climatic significance and thus warrant sustained measurements if at all possible. Sampling may not need to be at high-density but will usually be above the intermediate sampling of frequently repeated lines.

Finally, and perhaps most importantly, we need improved knowledge of such variability to test and develop models and as part of data assimilation parameterizations. As was pointed out at the start of this section, we are moving toward an era where *Argo* and altimetry provide the keys to understanding and monitoring ocean variability. Ocean models being developed for GODAE are likely to be eddy resolving. The issue then is how do we blend and integrate these different sources of information. "Assimilation" is usually the answer, but this glosses over the real problem. In the absence of adequate knowledge on mesoscale variability, it will be difficult to know how the coarse samples of *Argo* should be projected onto the eddy resolving fields of the model. In assimilation this is done through various parameterizations and assumptions about the ability of the model. These parameterisations and assumptions lie at the heart of data assimilation. A select number of high-density transects would not only help determine the spatial statistics of temperature and geostrophic velocity, but would also provide a means for "knitting" the various components of the observing system (particularly *Argo* and altimetry) together.

5.2.6 - Ocean state estimation

The requirements for seasonal-to-interannual forecasts and longer time scales are mostly covered above. It should be noted that ocean state estimates for longer time scales (Stammer et al, this Conference) do not, at this time, resolve mesoscale features and are thus unable to fully exploit high-density transects. However

the coherency of line sampling is a powerful constraint, as is the fact that the data can be assimilated safely in the knowledge that all relevant scales have been resolved in the original data.

At shorter time scales, GODAE does not have requirements that call for a unique contribution from SOOP other than the very important requirement related to data assimilation and parameterization (see the previous sub-section). Indeed, the aspects mentioned under 5.2.5 are perhaps as an appropriate characterisation of the requirements as we need. The focus on assimilation and estimation serves to highlight the need for SOOP lines that will assist in the blending and merging of different data sources.

GODAE does perhaps have a greater focus on the upper ocean and near-surface circulation. For mixed-layer depth, a mix of high-resolution transects (primarily there for other purposes) and *Argo* would seem an ideal mix.

The need for rapid dissemination of data is perhaps the unique twist that GODAE provides. In some cases, the cut-off is less than 24 hours which means the flow from instrument to users must be direct and automated. This does have some implications for quality - it comes after quantity in terms of priority.

5.2.7 - Climatologies and climate change

It is clear our knowledge of the mean and seasonal cycle of upper ocean temperature is not uniform through the world's oceans. In some places we have a good picture; in others our knowledge is scant. These gaps are mostly in places where our research vessels and SOOP do not go. There is no real expectation that this renovation of the SOOP can adequately redress this deficiency.

Implementation of *Argo* is likely to have a first order impact on our climatological data base. Around 100,000 extra temperature profiles per year, hopefully evenly spread through the world's oceans. The modern data base is not, however, simply about extracting the monthly means. It should contain reasonable estimates of the error, both in terms of the accuracy of the estimated signal and in terms of the "noise" about this mean (this tells a user how to interpret a single profile). It should also say something about the spatial coherence of the signal and about the spatial coherence of the noise. These are essential information for data assimilation. XBT transects are particularly useful for the spatial coherence estimates.

Section 7 discusses some of the data and information management issues. These have considerable bearing on the development of climatologies and a coherent, integrated database. For climate change, the emphasis has to be on high quality data sets. *Argo* seems to adequately address the issue of holes in our global sampling. The high-density east-west transects will address issues associated with trends in meridional exchange of heat.

6 - TOWARDS A NEW SOOP

The overarching guideline is that:

We should begin a phased reduction in areal sampling and an enhanced effort in line (transect) mode. The phased reduction in areal sampling will be determined by the schedule of implementation for Argo and the need for sufficient overlap to ensure that there are no systematic differences between XBT and float sampling. The line sampling will be built from the existing frequently-repeated and high-density modes of sampling. Where high density is

recommended the sampling density will be sufficient to resolve the Rossby radius and of around 3 month frequency. For frequently repeated sampling the sampling will be Rossby radius "detecting" [75-90 km] and repeated around every 3 weeks.

The key objectives of this new network will be

- a) To measure intraseasonal to interannual variability in the tropical oceans with a particular emphasis on the fine meridional structure and zonally-oriented currents. A secondary consideration is the provision of ocean data for the initialization of the next generation of seasonal-to-interannual prediction models.
Mode: FRX
- b) To measure the seasonal and interannual fluctuations in the transport of mass, heat and freshwater across ocean-spanning transects.
Mode: HDX
- c) To determine the spatial statistics of variability of the temperature and geostrophic velocity fields including the scale-dependent correlation of sub-surface temperature with surface topography variations (as measured by altimetry).
Mode: HDX
- d) To measure the temporal variability in boundary current regions and in the Antarctic Circumpolar Current through regular cross-current transects.
Mode: FRX, HDX
- e) To assist in the characterization of baroclinic eddies and other fine structure and thus estimate their significance for transport calculations and contribute to the determination of appropriate parameterizations for models and data assimilation.
Mode: FRX, HDX
- f) To the extent possible, and building on regional interests, contribute to studies of persistent small-scale features and to regional (large ocean area) measures of transport variability.
Mode: FRX, HDX

These goals are not intended to be unique to XBT sampling. For example, hydrographic sections contribute to the determination of transports and water masses. In such cases, the SOOP lines will assist determining the representation of the less-frequently repeated, but comprehensively sampled, sections.

We have resisted the temptation to write down "model testing" as a specific goal. All ocean data have a role in model testing. For the revised design, SOOP will provide data largely devoid of uncertainties due to inadequate sampling of the mesoscale and it is this attribute that will be most useful.

We have however emphasized the importance of these data in developing appropriate parameterizations for data assimilation.

The shift toward more intensive, line sampling does have implications for the way sampling must be done. Most high-density lines are sampled with the assistance of a scientist on board. This does have an advantage in that it can ensure a high-quality data return and facilitate additional measurements. It is this latter aspect that may be extremely important.

The revised frequently-repeated lines are shown in Figure 11 while the recommended high-density lines are shown in Figure 12. Highest priority lines are solid; second level priority dashed. More details on these

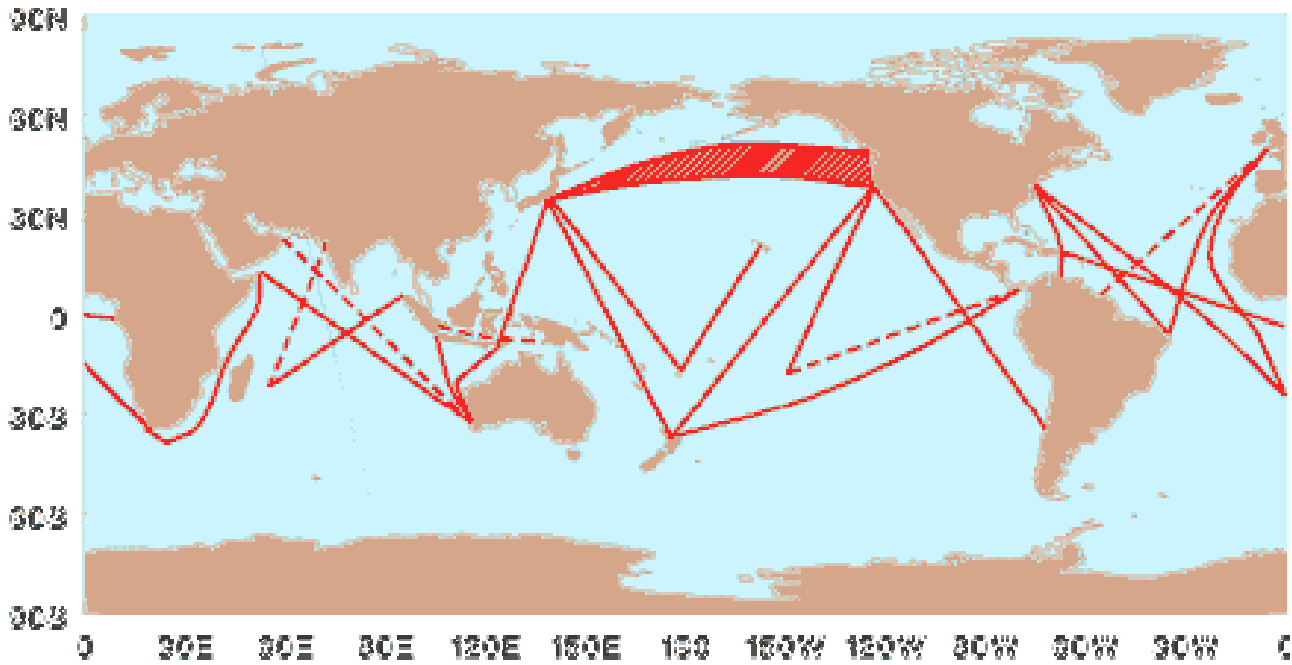


Figure 11. Proposed location of the frequently repeated lines. Note that this schematic is only a first draft and has not been discussed by all the relevant participants. Higher priority lines are drawn solid.

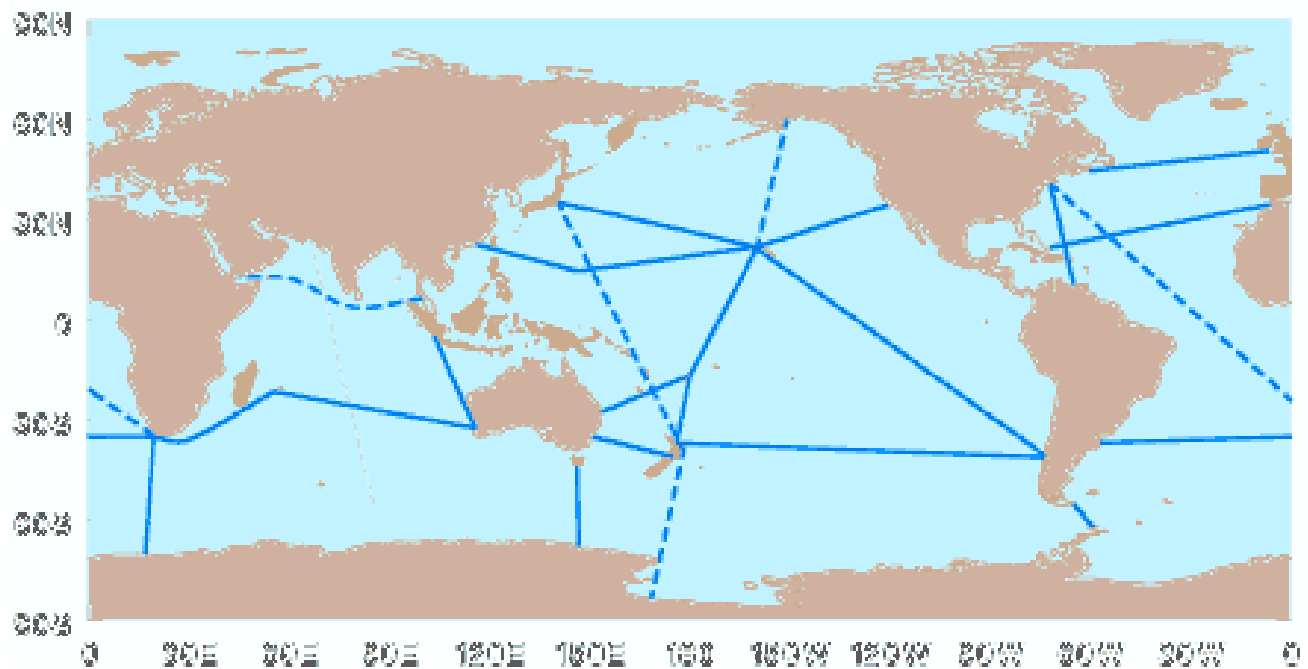


Figure 12. Proposed location of the density lines. Note that this schematic is only a first draft and has not been discussed by all the relevant participants. Highest priority lines are shown solid.

particular lines can be seen in Bailey et al (this Conference).

It can be seen that the majority of the frequently repeated lines intersect the tropical regions. The high-density lines are mostly for the determination of meridional heat transport and do are thus east-west. The exceptions are in the Southern Ocean, the Indonesian Throughflow and two lines in the Pacific which have a long history and provide some estimate of partitioning between the east and west. The frequently-repeated lines annually would require order 40% more probes for the same length of transect if the suggested spatial sampling is adopted.

A detailed costing has yet to be undertaken. The average cost of an XBT profile in low-density mode is variously estimated at between US\$120 to US\$170 per day. The cost per profile in HDX mode tends to smaller because reduced labor costs - US\$100-120 is a guide. FRX mode is somewhere in-between. No new lines have been added though several lines have been only irregularly sampled in the past (details are provided in the Workshop Report). In some cases HDX lines are also being occupied in FRX mode. The potential savings from moving toward less costly modes of sampling will be counterbalanced by the increase in the number of FRX and HDX lines and the increasing price of probes. The initial estimate is that a substantial fraction, if not all, of the new plan could be achieved with redeployment of existing resources. This may be difficult however as the resources are tied to nations and there is unlikely to be a zero-sum game for all nations.

7 - DATA ASSEMBLY AND MANAGEMENT ISSUES

This is an aspect that is not strictly within the remit of this paper, though it was included in the terms of reference of the study. Many of the details will be delayed until the Report of that study which includes a detailed analysis by Bob Keeley. However there are some issues that directly impact the effectiveness of the upper ocean network and that, moreover, could adversely impact the proposed new network if not addressed.

7.1 - Data delivery

Several of the applications and objectives discussed above place an extremely high premium on rapid delivery of data. Even in cases where delays can be tolerated there is wide agreement that rapid distribution is highly desirable. The accepted rule is

All upper ocean thermal data are to be distributed as soon as is practical after measurement (preferably 12 hours). The strong preference is to keep intervention to a minimum; perhaps just automated processes. There should be a well-supported second stream which allowed for improved quality control and scientific evaluation of the data sets.

These principles are effectively the same as those adopted by *Argo*. The fact that data are intended principally for a research goal does not mean that less attention should be given to rapid dissemination. The second stream is all about value-adding and quality control.

7.2 - Bandwidth and communications

At this point we remain constrained by available bandwidth from platform to shore. Many XBT data arrive in inflexion point form which precludes any high level of quality control (about 20% of such data are never replaced). A significant fraction of data transmitted over the GTS gets "lost" (order 5%). Furthermore, there are limitations on the depth and resolution. The move to line mode and the refocused scientific rationale places a high premium on the coherency of data sets and our ability to keep the original data intact. The present system does not appear well-suited to these tasks. Improved telecommunications and the possibility of two-way communications may alleviate some of these issues. However we must emphasize they still represent a significant constraint.

7.3 - Tracking data, auditing and accreditation

At the present time, we do not have a definitive ocean thermal data base. Indeed, for the various data sets that do exist it is difficult to ascertain the true commonality and genuine differences. One of the main reasons for this is our inability to track data - to provide a definitive audit trail by which any interested individual can track his copy of a profile back to its origins. The GTSPP format provides part of this facility through its History Record structure but it has not been adopted widely enough to have an impact. In general, it is simply impossible to tell whether two similar data did in fact originate from a single profile.

This problem is exacerbated by the lack of order in the value-adding chain. If a user is in possession of two records that she is sure originated from the same profile, but which have undergone two separate modes of quality control, which version does she retain and which does she discard? At present there is no guide for this decision. It is a situation that is compounded by the fact that we are still a little way off agreeing on quality control standards and nomenclature, despite the much fine work done in WOCE.

This is not simply an issue of metadata. It is mainly an issue of introducing some order and routine into the way we manage our valuable data.

Recommendation 1. A system of data "tagging" should be instituted immediately. Every original piece of data would be issued a unique identifier, much as an email message receives a unique tag depending upon where it originated and when and where it entered the internet. This tag would never be separated from the data, no more than you would separate data from its location and/or time. Any data without a tag would be classed as non-data. Any subsequent processor would add further identifying information but would leave the original tag in place.

Recommendation 2. A system of quality accreditation would be introduced in order to better identify and credit value adding. Scientific quality control would be at the high-end of this accreditation and would, by definition, involve scientific involvement in the evaluation of quality. One would expect WOCE DACs to be in this category. There may be 3 or 4 other levels down to rapid, automated QC and no QC. Each processor would be obliged to note the level (of accreditation) on data that re-entered circulation.

With these pieces of information it would be possible for users to first identify without confusion duplicates, and to choose a level of QC that was appropriate to his application.

In keeping with distribution guideline, it may be useful to develop the concept of a continuous circuit of data with individuals and groups adding, copying and replacing data on the circuit. The user then could, in principle, copy off the highest quality thermal data for a particular region.

7.4 - Toward a definitive ocean thermal data base

Without the actions noted in 7.3, the notion of a definitive data base is probably no more than that - notional. It is impossible to totally eliminate replications and errors in the present data sets, this in spite of the dedication of many to these tasks. This is an embarrassment for our community, the fact that we cannot point to a data base that all would agree was an up-to-date representation of our gathered knowledge.

We suggest this be addressed by first putting in place the auditing and accreditation system noted above. At the highest level (high in terms of data set quality) we would designate and/or invite a centre to assume responsibility for the assembly of a definitive data set, in cooperation with those other centres dedicated to improved data sets. The basic premise is that scientific quality control *does* add considerable value to data sets and that, as a consequence, we should do all we can to ensure this value-adding is not subsequently lost or degraded. The definitive data set would be constructed according to the accreditation system and would be global. At present, the closest we have to this is the research team led by S. Levitus.

8 - CONCLUSIONS

This paper describes the past experience with XBT sampling from the ship of opportunity program. It notes that, till this point of time, sampling had been in three modes: low density, frequently repeated and high density. The SOOP has been extremely cost-effective for science and, latterly, for operational applications. However it is reasoned that it is timely to consider a change of direction and a new focus.

This paper is proposing a major revision of the ship-of-opportunity program. The program would gradually withdraw from areal sampling as *Argo* was implemented, and would at the same time ramp up its effort in line (transect) sampling. The line sampling would include both intermediate resolution, frequently repeated lines and high density, quarterly repeat lines. We argue that this change in approach enhances complementarity with existing elements, particularly TAO and altimetry, and seeks optimum complementarity for the system envisaged for the future.

The new design will address several important scientific goals, both for GOOS and CLIVAR. It will make unique contributions in terms of in situ eddy-resolving data sets and in terms of the repeated lines.

It is estimated that this new design will not have significant resource implications. We note that this new mode of operating does open up further opportunities for observations from SOOP though this has to be balanced against the good-will being offered by the ships.

Several recommendations are also made with respect to data management. It is argued that present arrangements proscribe against efficient and effective use of the data.

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