The Ship Of Opportunity Program

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Summary.

A multi-national review of the global upper ocean thermal networks was carried out in 1999, with results and recommendations reported at the OceanObs99 conference (Smith et al, 2001). Anticipating implementation of the Argo float network, a primary recommendation of the review was an evolution from broad-scale eXpendable BathyThermographs (XBT) transect sampling to increased spatial and temporal transect-based sampling modes. The transect modes (Low Density, Frequently Repeated, and High Density) sample along well-observed transects, on small spatial scales, or at special locations such as boundary currents and chokepoints, all of which are complementary to Argo's global broad scale array. An objective of the present paper is to review the present status of networks against the objectives set during OceanObs99, to present key scientific contributions of XBT observations, and new perspectives for the future. Currently with the evolution of the XBT network, techniques for analyzing and synthesizing the datasets, including ocean data assimilation modeling, have progressed substantially. The commercial shipping industry has itself developed in the past decade, toward fewer routes and more frequent changes of ships and routing. In spite of these changes, many routes now have, in addition to XBT sampling, measurements from ThermoSalinoGraph (TSG), eXpendable Conductivity Temperature and

Depth (XCTD), partial CO_2, Acoustic Doppler Current Profiler (ADCP), Continuous Plankton Recorders (CPR), marine meteorology, fluorescence, and radiometer measurements. The ongoing value of the Ship Of Opportunity networks is viewed through their extended time-series and their integrative relationships with other elements of the ocean observing system including, for example, profiling floats, satellite altimetry, and air-sea flux measurements. Improved capabilities in ocean data assimilation modeling and expansion to support large scale multidisciplinary research will further enhance value in the future. Recent studies of XBT fall rate are being evaluated with the goal of optimizing the historical record for global change research applications.

1. Introduction: The OceanObs99 recommendations.

EXpendable BathyThermographs (XBTs) are widely used to observe the thermal structure of the upper ocean and constitute a large fraction of the archived ocean thermal data during the 70s, 80s and 90s. Prior to the OceanObs99 meeting, a white paper (Smith et al, 2001) was written to examine the status of XBT observations and to provide recommendations on how to proceed with XBT observations and analyses after implementation of the Argo program. Until the advent of the Argo array, XBTs constituted 50% of the global ocean thermal observations, providing sampling along major shipping lines. While the Argo array now provides temperature profile observations with an homogeneous distribution globally, the XBT observations are carried out mostly along fixed transects. Currently, XBTs represent approximately 25% of current ocean temperature profile observations.

OceanObs99 made recommendations on three modes of deployment: High Density (HD), Frequently Repeated (FR), and Low Density (LD). The requirements for each of these three modes of deployment are:

1. **Low Density**: 12 transects per year, 4 XBT deployments per day,
2. **Frequently Repeated**: 12-18 transects per year, 6 XBT deployments per day (every 100-150 km), and
3. **High Density**: 4 transects per year, 1 XBT deployment every approximately 25 km (35 XBT deployments per day with a ship speed of 20kts).

OceanObs99 made recommendations for transects in FR and HD modes, but not for LD mode. The LD mode was recommended to be evaluated and to slowly be phased out if Argo profiling float data could provide the same type of information. The FR and HD modes are both aimed at obtaining high spatial resolution observations. HD transects are designed to have high spatial resolution in one single realization, while FR transects accomplish the same objective from consecutive realizations. Details of the goals of each mode and of specific transects are provided by Smith et al [2001]. The current XBT transects somewhat differ from the OceanObs99 recommendations. Therefore, several questions remain to be addressed 1) If the present sampling satisfies the needs of the scientific and operational communities, 2) whether there is any impact on science and operations because of these differences, and 3) how these issues will be addressed.

The following are the XBT recommendations from OceanObs99 and their current status:

1) Recommendation: Begin a phased reduction in LD sampling and an enhanced effort in FR and HD sampling. Status: LD network has been reduced, HD network has been enhanced and FR transects remain essentially constant.

2) Recommendation: Base the phased reduction in LD sampling on the implementation of Argo and have sufficient overlap to ensure that there are no systematic differences between XBT and float sampling. Status: Although some LD transects have been discontinued before adequate analyses have been performed, there are several ongoing studies addressing this issue. LD transects that have been occupied for 40+ years are being reviewed to determine if they provide information on decadal variability in temperature characteristics of the subtropical and subpolar gyres. For example, AX10 shows decadal meridional migrations of the Gulf Stream (GS) correlated with the North Atlantic Oscillation (NAO), GS transport and size of the southern recirculation gyre (Molinari, 2003). AX03, where the GS joins the North Atlantic Current (NAC) shows decadal variability correlated with that at AX10 (Molinari, 2009, in preparation). AX02 cuts across the northern NAC as it turns anticyclonically and also provides evidence for decadal variability farther downstream in the boundary current system. These last two transects are no longer occupied regularly and until the Argo array and satellite altimetry show that they can provide similar results it is recommended that data collection be restarted.

3) Recommendation: Build the FR and HD network on existing transects. Status: Underway.

4) Recommendation: Data are to be distributed within 12 hours, with minimal intervention. Status: After consultation with operational groups time limit was changed and implemented to 24 hours using automatic quality control tests.

5) Recommendation: Perform delayed mode quality control (QC) with improved QC tests. Status: Initially accomplished at three centers (the Atlantic Oceanographic and Meteorological Laboratory, Australian Commonwealth Scientific and Industrial Research Organisation, and Scripps Institution of Oceanography) under auspices of the Global Temperature-Salinity Profile Program (GTSPP). GTSPP, the long term archival center of the XBT network data, performs the delayed-mode QC tests originally done by the three science

centers, but later performed using the Integrated Global Ocean Services System (IGOSS) flags by the US National Oceanographic Data Center and by the World Ocean Database (WOD).

6) Implement improved communications allowing for full depth resolution transmission. Status: Partially accomplished. It is still needed to be evaluated whether the operational community needs full depth resolution profiles in real-time.

7) Implement a system of data tagging that will provide a unique identity that will supply a unique identity to each profile. Status: Partially implemented by all centers.

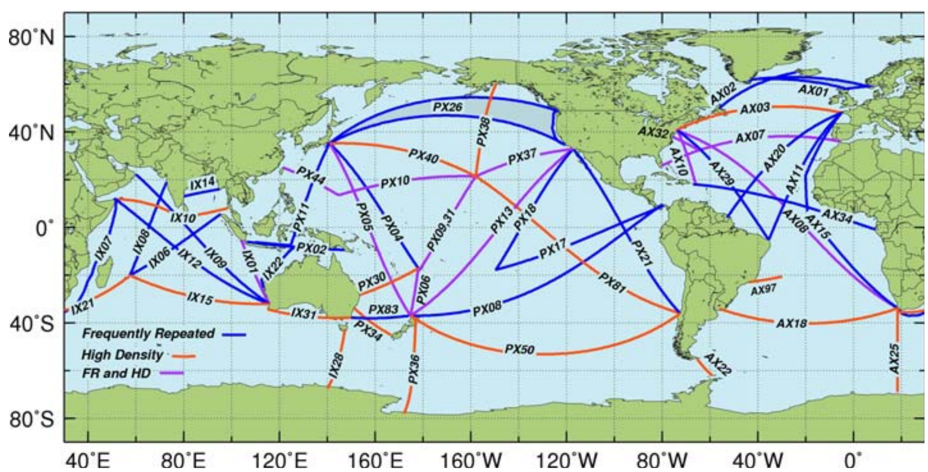
8) Recommendation: Implement a system of data quality accreditation in order to better identify data originators if modification of data is needed. Status: Not yet implemented. Transmission format will start changing in 2011 to Binary Universal Form for the Representation of data (BUFR) to accomplish this.

9) Recommendation: Develop a definitive ocean thermal database. Status: GTSPP was initiated to change the management of ocean profile data. The program is founded on the principle of a continuously managed database so that at any time a user may have the most up-to-date, highest resolution, highest quality data available at the time of the request. To achieve this, GTSPP instituted standards for data quality, data structures, and project reporting procedures. GTSPP in collaboration with the Ship Of Opportunity Program (SOOP) is testing the use of unique data identifiers as a way to more effectively identify and so control data duplication and has initiated support for the Joint World Meteorological Organization (WMO) – Intergovernmental Oceanographic Commission (IOC) Technical Commission for Oceanography and Marine Meteorology (JCOMM) quarterly reports providing the information on temperature and salinity profiles. GTSPP has built an international partnership that has served as a model for managing other kinds of data.

2. The Ship Of Opportunity Program.

The SOOP addresses both scientific and operational goals for building a sustained ocean observing system. These subsurface data are used to initialize the operational seasonal-to-interannual (SI) climate forecasts and have been shown to be necessary for successful SI predictions. Other key uses of these data are to increase understanding of the dynamics of the SI and decadal time scale variability, to perform model validation studies, and to investigate meridional heat advection at the basin scale. The Ship Of Opportunity Programme

Implementation Panel (SOOPIP), an international World Meteorological Organization (WMO)-Intergovernmental Oceanographic Commission (IOC) program, has as a primary objective to fulfill the XBT upper ocean data requirements established by the international scientific and operational communities. The annual assessment of transect sampling is undertaken by the Joint WMO-IOC Technical Commission for Oceanography and Marine Meteorology (JCOMMOPS) on behalf of SOOPIP. While SOOPIP deals with ocean observations, the VOS (Volunteer Observing System) Programme deals with meteorological observations [please refer to Community White Paper on VOS]. Besides carrying out the deployment of XBTs, some ships of the SOOP have other instrumentations installed [Please refer to Community White Paper on Underway Observations] and are also used to deploy Argo profiling floats and surface drifters.



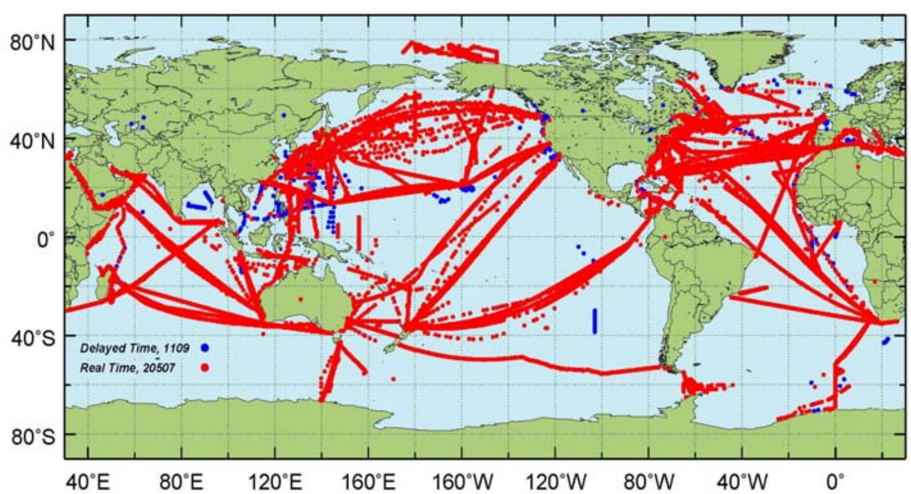


Figure 1. (top) XBT network containing OceanObs99 recommendations (after Smith et al, 2001) and current proposed transects. (bottom) XBT observations transmitted in (red) real- and (blue) delayed-time in 2008. The real-time data were obtained from the (Global Telecommunication System (GTS) and the Coriolis data center. The delayed-time data were obtained from the Global Temperature and Salinity Profile Programme managed by NOAA/NODC.

3. XBT deployments.

The scientific and operational communities deploy approximately 23,000 XBTs every year. In a typical year 50% are deployed in the Pacific Ocean, 35% in the Atlantic Ocean and 15% in the Indian Ocean. Profiles from about 90% of the XBT deployments are transmitted in real-time, which represent around 25% of the current real-time vertical temperature profile observations (not counting the continuous temperature profiles made by some moorings).

A comparison between the recommended and actual transects and deployment modes reveal that:

a) Most transects are being carried out as recommended by OceanObs99,

b) Some deployments are being done along transects that were not recommended,

c) Some deployments are not done along transects that were recommended, and

d) Only a few recommended transects are being partly done.

a) Low Density transects

In view of the implementation of the Argo Program and, to some extent, of the availability of satellite altimetry data, the international SOOP community decided in 1999 to gradually phase out the transects made in LD mode, but to maintain the transects in HD and FRX modes. This reduction was to be made if observations from Argo floats revealed that they could reproduce the same type of upper ocean thermal signals revealed by those from XBTs deployed in LD mode. However, the actual reduction in LD sampling started in FY2006 and without this type of study being finalized, when several low density transects were dropped and others were converted to FR transects. The reasoning behind these selections was two fold: 1) To keep the transects that had been operating the longest, and 2) To maintain transects (mostly meridional) that cross the Equator and that are located in the subtropics in view of the SI emphasis for the use of the XBT observations. It is important to notice that some LD transects were dropped before Argo was fully implemented, as some may also argue that there should have been an overlap period between LD XBT deployments and fully implemented Argo to investigate if Argo can reproduce the same type of signals that XBTs do in this mode of deployment.

Low density transects have both operational and scientific objectives, some of which are:

- Investigate intraseasonal to Interannual variability in the tropical oceans,
- Measure temporal variability of boundary currents, and
- Investigate historical relationship between sea height and upper ocean thermal structure.

Illustrative examples of applications of XBT observations, primarily from LD mode, are:

- The time series of the position of the Gulf Stream beginning in the early 1950s by combining mechanical bathythermograph data with XBT data along AX10 (Figure 13 in Molinari, 2004). These results agreed with Gulf Stream positions over a 1000km swath previously developed [Joyce et al, 2000]. These results also showed that the meridional migrations of the Stream were closely correlated with the North Atlantic Oscillation (NAO) on decadal time-scales (Figure 13 in Molinari, 2004). The axis translations were also similar to anomalies in Gulf Stream upper layer transport and east-west extension of the Stream's southern recirculation gyre.
- The long term evolution of the volume and spatial extension of the warm waters of the western equatorial Pacific Ocean in relation with the interannual and decadal variability of ENSO. Toole et al [2004] and Cravatte et al. [2009] have shown that the Warm Pool volume expanded drastically during the past decades, a modification that may represented up to a 60% increase of the Warm Pool volume. Changes in the surface and subsurface conditions of the warm waters of the equatorial Pacific are important to alter the local air–sea interactions [Maes et al., 2006] and to maintain the heat buildup prior to El Nino development [Meinen and McPhaden 2000; Maes et al. 2005].
- In a study of all available XBT observations from 1993 until 1999 it was observed that altimeter-derived sea heights are not always directed correlated to dynamic height, possibly due to opposite thermal effects in the water column [Mayer et al, 2003; Mayer et al, 2001].

b) Frequently Repeated transects.

The FR transects cross major ocean currents systems and thermal structure. In some cases, for currents near a continental boundary an extra profile is made at crossing the 200m depth contour to mark the inshore edge of the current. The FR transects are selected to observe specific features of thermal structure (e.g. thermocline ridges), where ocean atmosphere-interaction is strong. Estimates of geostrophic velocity and mass transport integrals across the currents are made by low pass mapping of temperature and dynamical properties on the section. Frequent sampling is recommended in regions that have strong intra-seasonal variability to reduce aliasing. The FR transects must be on well defined shipping routes so that the same transect is very nearly covered on each repeat-transect. The proto-types of FR transects are IX01 and PX02, which now have time series extending more than 20 years. The earliest transect (from Fremantle to Sunda Strait, Indonesia) began in 1983 and has been sampled at 18 times per year most of the time since 1986. IX01 crosses the currents between Australia and Indonesia, including the Indonesian Throughflow and has been used in many studies of the Throughflow and the Indian Ocean Dipole. Most of the implemented and analyzed FR transects are located in the Indian Ocean and Indonesian Seas where the intra-seasonal variability is strong.

The scientific objectives of FR transects and recent examples of research targeting these objectives are:

- Measure the seasonal, interannual, and decadal variation of volume transport of major ocean currents [Wainwright et al. 2008; Wijffels et al. 2008; Potemra, 2005; Sprintall et al. 2002].
- Characterization of seasonal and interannual variation of thermal structure and their relationship with climate and weather [Sakova et al. 2006; Cai et al. 2005; Qu and Meyers 2004; Feng and Meyers 2003; Rao et al. 2002; Meyers, 1996; Gopalakrishna et al. 2003].
- Identify the relationship between sea surface temperature, depth of the thermocline and ocean circulation at interannual to decadal timescales [Alory and Meyers 2009; Du et al. 2008; Alory et al 2007; Qu et al. 2004].
- Rossby and Kelvin wave propagation [Wijffels and Meyers 2004; Masumoto and Meyers 1998].
- Validation of variation of thermal structure and currents in models [Cai et al 2005; McClean et al. 2005; Schiller 2004].

The CLIVAR/GOOS Indian Ocean Panel (IOP) reviewed XBT sampling in the Indian Ocean and prioritized the transects according to the oceanographic features that they monitor [CLIVAR Project Office, 2006]. The highest priority was given to transects IX01 and IX08. The IOP recommended weekly sampling on IX01 because of its importance for monitoring the Indonesian throughflow and to resolve the strong intra-seasonal variability in the region.

Data obtained from IX08 is used to monitor flow into the western boundary region, and the Seychelles-Chagos Thermocline Ridge, a region of intense ocean-atmosphere interaction at inter-annual time scales [Vialard et al. 2008; Xie et al. 2002]. IX08 has proven to be logistically difficult so an alternate transect may be needed. The IOP placed lowest priority on IX07 because the line does not cut across currents, but rather runs in the same direction of the currents, thus sampling only the energetic eddies in this region. For this reason this transect does not suit the FR and HD goal of observing basin-scale geostrophic velocity and mass transport integrals. The oceanographic features that need to be observed with FR sampling on IX06, 09, 10, 12, 14 and 22 (Figure 1) are identified in the IOP report.

The FR sampling produces well resolved monthly time series of thermal structure along transects. Using IX01 as an example, the mean thermal structure (Figure 2) indicates the generally westward flow in the deeper part of the thermocline, and a shallow (<150 m) eastward shear [Meyers et al, 1995]. The strongest variability in temperature is at the northern end of the transect near Indonesia (Figure 2, top right). The temperature sections were used to understand the relationship of interannual variation in transport of Indonesian Throughflow to El Nino Southern Oscillation [Meyers, 1996]. An example of time-variation of temperature at the north end of IX01 (Figure 2) clearly shows the strong, subsurface upwelling associated with the start of the IOD events of 1994 and 1997, before the start of surface cooling. These and the other FRX time series have been used to understand how subsurface thermal structure varies across the Indian Ocean during Indian Ocean Dipole (IOD) events [e.g. Rao et al. 2002; Feng and Meyers, 2003], and more recently, combined with coupled models to understand predictability of the IOD [Luo et al., 2007]. Use of FR lines in the Indonesian region to study the Indonesian Through-flow [Meyers et al. 1995; Meyers, 1996; Wijffels and Meyers, 2004; Wijffels, Meyers and Godfrey, 2008] is discussed in the Indian Ocean white paper [Masumoto et al., 2009].

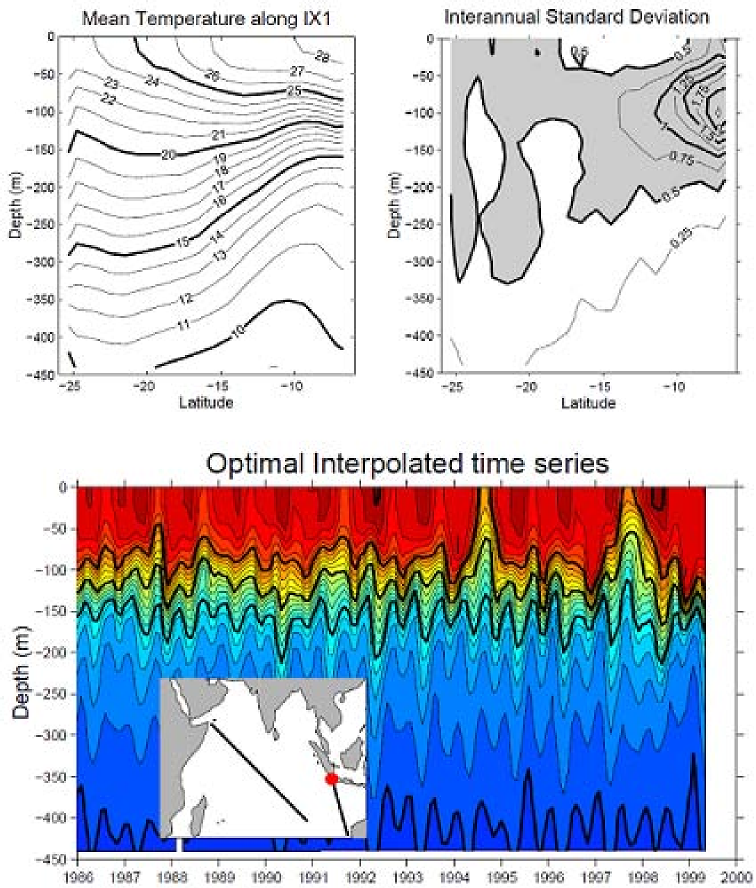


Figure 2. (top left) Mean and (top right) standard deviation of temperature on IX1. (Bottom) Temperature on IX01 1985 to 1999.

c) High Density transects.

The HD transects extend from ocean boundary (continental shelf) to ocean boundary, with temperature profiling at spatial separations that vary from 10 to 50 km in order to resolve boundary currents and to estimate basin-scale geostrophic velocity and mass transport integrals. Most HD transects are carried out 4 times per year, and many now have time-series extending for more than 15 years. PX06 (Auckland to Fiji), which began in 1986, is the earliest HD transect in the present network with more than 90 realizations. Some transects are being assessed for their contribution in this mode. For example, the CLIVAR IOP noted that further work is required to assess the value of IX10, which transects the openings of the Bay of Bengal and the Arabian Sea. Scientific objectives of HD sampling, and examples of research targeting these objectives are:

- Measure the seasonal and interannual fluctuations in the transport of mass, heat, and freshwater across transects which define large enclosed ocean areas and investigate their links to climate indexes [e.g. Roemmich et al, 2001, Roemmich et al., 2005, Douglass et al., 2009a, Garzoli and Baringer, 2007, Baringer and Garzoli, 2007; Dong et al, 2009].
- Determine the long-term mean, annual cycle and interannual fluctuations of temperature, geostrophic velocity and large-scale ocean circulation in the top 800 m of the ocean [e.g. Lentini et al, 2006, Swart et al, 2008, Morris et al. 1996, Murty et al, 2000, Roemmich and Sutton, 1998, see also Figure 3]. However, in some regions, XBTs reaching 800m cannot depict the complete vertical structures of fine but intense oceanic jets [Gourdeau et al., 2008] and a combined approach in term of high density and deep enough measurements will be very valuable.
- Obtain long time-series of temperature profiles at precisely repeating locations in order to unambiguously separate temporal from spatial variability (e.g. Sutton et al., 2005)
- Determine the space-time statistics of variability of the temperature and geostrophic shear fields [e.g. Gilson et al., 1998].
- Provide appropriate *in situ* data (together with Argo profiling floats, tropical moorings, air-sea flux measurements, sea level etc.) for testing ocean and ocean-atmosphere models [e.g. Douglass et al., 2009b].
- Determine the synergy between XBT transects, satellite altimetry, Argo, and models of the general circulation [e.g. McCarthy et al., 2000; Goni and Baringer, 2002].
- Identify permanent boundary currents and fronts, describe their persistence and recurrence and their relation to large-scale transports [e.g. Gilson and Roemmich, 2002, Ridgway and Dunn, 2003; Goni and Wainer, 2001].
- Estimate the significance of baroclinic eddy heat fluxes. [e.g. Roemmich and Gilson, 2001].

The present HD network (Figure 1) and the primary country/institution and major partnerships, and the year when sampling began (Table I) is a reflection of the international effort behind these transects. Some transects are currently inactive due to implementation (usually ship recruitment) issues but alternative transects are carried in their places, such as the cases of PX50/PX08 and AX18/AX17. Other transects, such as IX21 and IX15, have had multi-year interruptions. Detailed sampling histories and data are available at http://www-hrx.ucsd.edu and http://www.aoml.noaa.gov/phod/hdenxbt. Data are made available through these web sites as individual transects because it is difficult to retrieve them as transects from national data centers. Data from current HD transects are frequently used for research purposes, which strongly argues for continuing maintenance of these transects. Four illustrative examples are presented here to show key scientific results obtained from HD transects:

1) Temperature and geostrophic current variability in the southwest Pacific Ocean.

XBT profiles obtained along PX06 provide typical results from high density transects, such as the 20-year mean and variance of temperature [Sutton and Roemmich, 2001], mean geostrophic velocity, and time series of net geostrophic transport (Figure 3). The high value of this long time-series is seen in several ways. First, the 20-year mean velocity shows that the eastward flow from the separated western boundary current occurs in distinct permanent filaments [Figure 3 and Ridgway and Dunn, 2003], demonstrating the banded nature of the mean velocity field; these filaments are also visible in all 5-year subsets. Second, the existence of minima in temperature variance at both ends of the transect indicates that geostrophic transport integrals spanning the entire transect have less variability than any partial integrals. Third, the HD-XBT network design, which in this particular case encloses a region with boundary-to-boundary sampling, provides closed mass and heat budgets for the upper ocean [Roemmich et al., 2005]. Fourth, the transport time-series shows variability with a period of about 4 years and a sudden change. This change is consistent with decadal changes in wind stress that are believed to have caused the East Australian Current to extend farther southward [Cai et al., 2005]. Finally, the PX06 transect has contributed to understanding the formation, spreading, characteristics and variability of South Pacific Subtropical Mode Water [e.g. Roemmich and Cornuelle, 1992, Tsubouchi et al., 2007, Holbrook and Maharaj, 2008].

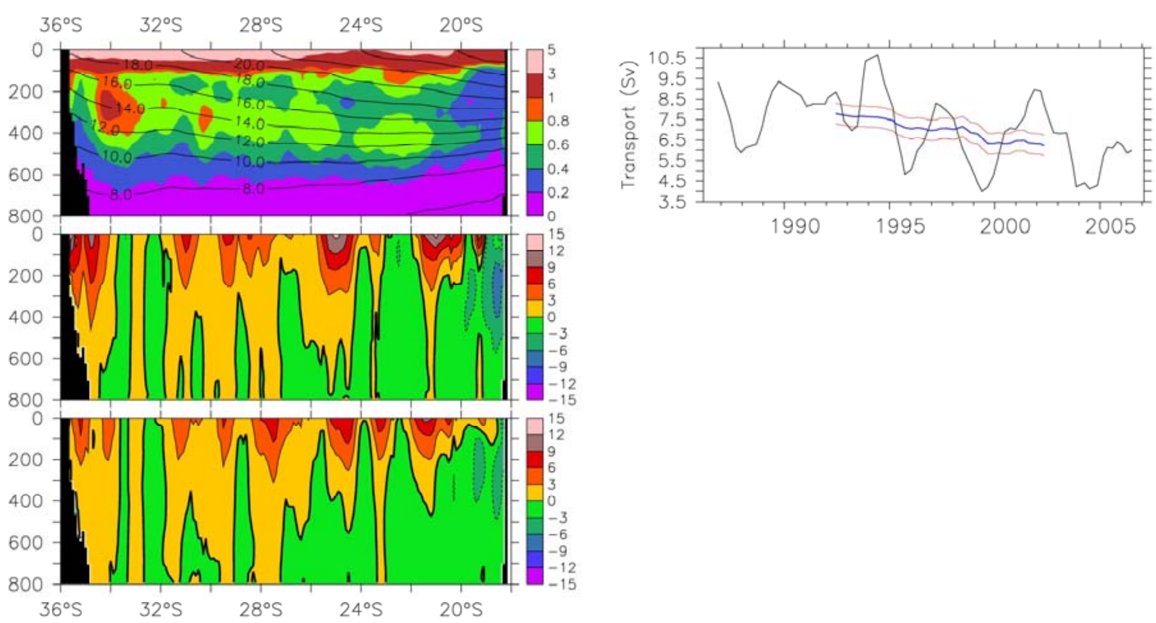
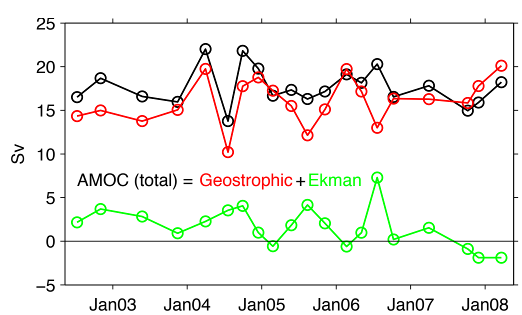


Figure 3. (left top) 22-year mean (1986-2007, contours) and variance of temperature (colors) from HD XBT transect PX06, Auckland to Fiji. The 11-year means of geostrophic velocity (cm/s) are shown for (left center) 1986-1996 and (left bottom) 1997-2007. (right) Time-series of geostrophic transport (Sv), 0-800 m. The black line is a 1-year (4 cruise) running mean; blue is a 10-year running mean with 1 standard error limits in red.

2) Atlantic Meridional Overturning Circulation studies

In the Atlantic, the two zonal HD transects AX18 and AX07 are being used to assess the strength of northward heat transport. The AX18 transect is designed to monitor the upper limb of the Atlantic Meridional Overturning Circulation (AMOC) as it enters the South Atlantic at approximately 35°S, between South Africa and South America. During the period July 2002 – March 2009, twenty one realizations of this transect have been carried out. Results from these HD transects show that the northward heat transport across 35°S is approximately 0.54+/-0.11 PW. A clear seasonal cycle was found for the geostrophic and Ekman heat transport, which have similar amplitude but are close to 180^{o} out of phase, therefore explaining the small seasonal cycle in the total northward heat transport. This northward heat transport is directly linked to the strength of the MOC that shows a similar out of phase relationship between Ekman transport and Sverdrup transport (Figure 4, left). In the north Atlantic, the HD transect AX07 is being analyzed to estimate the northward heat transport. Results have shown that the northward transport (computed using the methodology introduced by Baringer and Garzoli, 2007) has a remarkable out of phase relationship to important climate indices, such as the Atlantic Multidecadal Oscillation (AMO). Results also show that the net northward heat transport through the center of the subtropical gyre in the North Atlantic is negatively correlated to the AMO index (for time scales longer than 2 years) (Figure 4, right). The AX07 transect is also being used to estimate eddy heat transports in association with the Rapid/MOCHA Program, which is in place to measure the MOC at 26^{o}N.



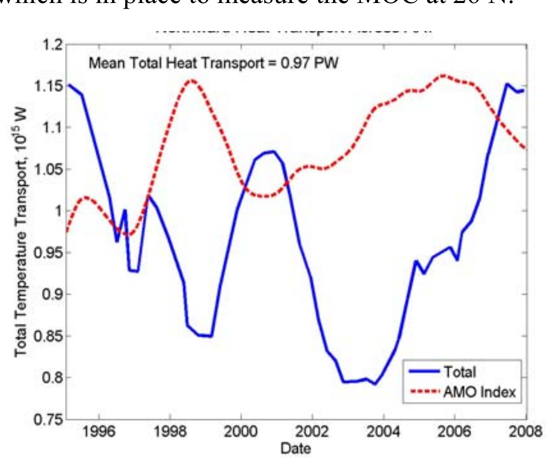


Figure 4. (left) Time series of the AMOC (black) estimated from AX18 and contributions from the geostrophic (red) and Ekman (green) components [from Dong et al, 2009]. (right)Northward heat transport (blue line) across the high density (HD) transect AX07 that includes coast to coast observations from Spain to Miami compared to the Atlantic Multidecadal Oscillation (AMO) index (red dashed line).

3) Variability of the Antarctic Circumpolar Current

The high density XBT transect along AX25 (between Cape Town and Antarctica) provides detailed information on the varying physical structure of the upper ocean across the widest 'chokepoint' (>4000 km) of the Southern Ocean. These observations are extremely important in the region due to the scarcity of hydrographic observations in the South Atlantic Ocean. In recent years, proxy techniques have been employed to provide additional oceanographic information from XBT profiles. Along the AX25 transect, XBT data are used to construct empirical relationships whereby baroclinic transport estimates of the Antarctic Circumpolar Current (ACC) can be derived from altimetry data alone. These estimates have been a major aim of oceanographers in the past. These methods allow us to study a 16-year long, weekly time series of ACC transports (Figure 5), which reveal the internal variability of the ACC system. Additionally, XBTs deployed in HD mode have uncovered, in more detail, the fine scale jets and fronts that make up the total circumpolar flow in this region (Swart et al., 2008). Interestingly, the Subantarctic Front contributes to over 50% of the total transport variance of the ACC over the time series, even though its net transport contribution is less than other fronts. In time, supplementary XBT deployments will be used to validate and improve this range of methods that are required in data sparse regions.

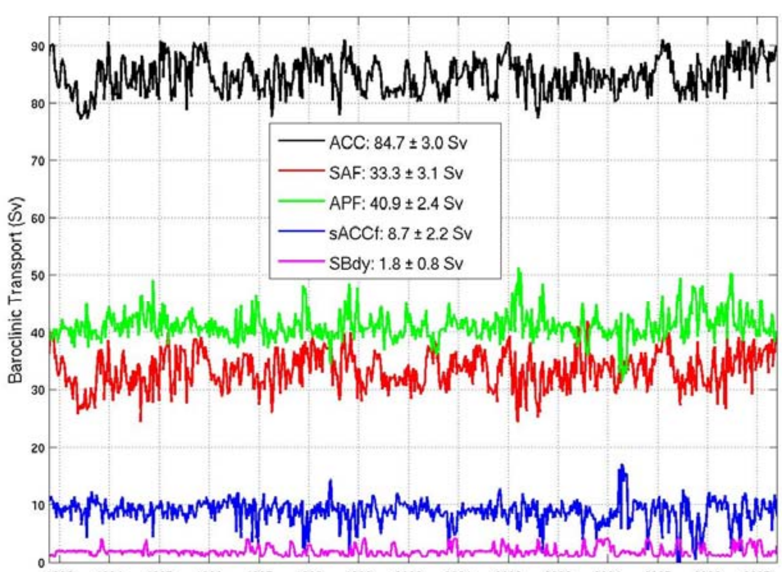


Figure 5. Time series of baroclinic transport estimates, relative to 2500 dbar, for each ACC front and for the whole ACC domain between 1992 and 2007 (taken from Swart et al., 2008). These transports are estimated from altimetry data using proxy techniques constructed from CTD and XBT data along the AX25 hydrographic transect. The legend depicts the mean and standard deviation of the transport time series for each respective domain.

3) Temperature and geostrophic current variability in the Bay of Bengal

Utilizing a twenty year (1989 – continuing) time series of XBT data collected by the National Institute of Oceanography, India, surface and subsurface temperature changes were used to investigate a) if the subsurface North Indian Ocean is affecting a possible amelioration of the increase SST, and b) if the Arabian Sea and the Bay of Bengal exhibit opposing behavior with respects to ocean heat content, with one cooling and the other warming, resulting in no obvious trend in ocean heat content. Preliminary results show that temperature anomalies [for the shaded box in Figure 6a] at the sea surface and at 600 meters depth exhibit significant increasing trend (Figure 6b) while the temperature anomaly at 100 meters (nearly representing thermocline depth) exhibits strong year to year variability with no long term trends (Figure 6c). This study was performed using only data from XBT transect IX14. This data set contains 20 years of consistently collected time series data using XBTs. Using this one consistent data set removes the complication of separating real physical change in the temperature structure of the Bay of Bengal from changes which may be introduced by differences in instrumentation and collection procedures. Preliminary results using Argo float data show a slight decrease in the upper ocean heat content of the Bay of Bengal [Uday Bhaksar, personal communication], which is consistent with our results. Using the two datasets can independently support results, at least for the last few years and into the future. This type of study can only be performed using the long-time series provided by the XBT transects in the Bay of Bengal. Maintaining the transects will extend this work into the future and provide crucial information on climate change in the North Indian Ocean.

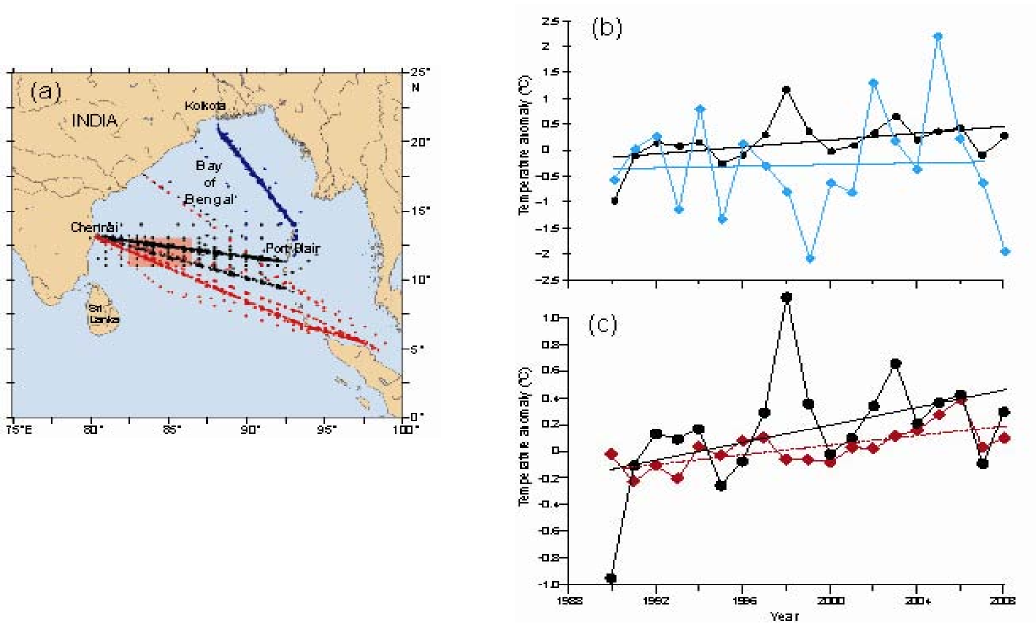


Figure 6. (a) XBT transects in the Bay of Bengal (1989-2008); (b) year to year changes in temperature anomalies at the surface (black) and 100m (blue); and (c) for the shaded box in (a) for the surface (black) and 600m deep (red).

4. Data Management.

The data management activities of the program continue to be undertaken in collaboration with the Global Temperature and Salinity Profile Programme (GTSPP). The GTSPP is a joint program of the International Oceanographic Data and Information Exchange committee (IODE) and the Joint Commission on Oceanography and Marine Meteorology (JCOMM). The Integrated Scientific Data Management of Canada accumulates near real-time data from several sources via the GTS, checks the data for several types of errors, and removes duplicate copies of the same observation. These operations occur three times per week before passing the data on to the Continuously Managed Database (CMD) maintained by the U.S. National Oceanographic Data Center (NODC). The data flow into the CMD is through a "Delayed Mode Quality Control (QC)" process. This process includes format conversion, format-consistency test, authority tables' check, and duplicate check for the GTSPP database. The NODC replaces near real-time records with higher quality delayed-mode records as they are received and populates the GTSPP data on-line through the GTSPP Web site at http://www.nodc.noaa.gov/GTSPP. The unique features of GTSPP include: (1) unify all temperature (T) and salinity (S) profile data into a common structure and therefore a common output, which is inter-operatable and extendable, (2) set standards for quality control of T and S profile data, (3) document data processing history, and (4) provide ship operators with monthly reports of data quantity and quality assessment, and (5) carry complete metadata descriptions of every record. Readers should refer to the Community White Paper describing the GTSPP operations for greater detail.

5. XBT Biases.

The determination of the XBT depth is the most important source of error in XBT temperature profiles [Wijffels et al, 2008] although other sources of error exist (e.g temperature offsets, recording errors, etc). Unlike Argo observations, XBTs determine the depth of the temperature observations indirectly from a time trace converted into depth using a fall-rate equation (FRE). This FRE results from a simple dynamical model where the net buoyant force is balanced by hydrodynamic drag proportional to the square of the probe speed [Green, 1984; Hallock and Teague, 1992]. The fall speed is virtually equal to the terminal velocity, a reasonable assumption for depths larger than 10 m. The bulk of XBT temperature profiles are collected using probes manufactured by Sippican Incorporated (now Lockheed Martin Sippican). Systematic errors in the computed XBT depths have been identified since the mid 1970s: Early comparison studies between simultaneous XBTs and Conductivity Temperature Depth (CTD) casts found a small positive bias above the thermocline, while a much larger negative bias for depths below [Fedorov, 1978; Flierl and Robinson, 1977; McDowell, 1977; Seaver and Kuleshov, 1982] demonstrating the limitations of the original FREs. Evidence of surface offset associated with initial transients has also been found [Singer, 1990; Kizu and Hanawa, 2002]. Nonetheless, XBT temperature profiles have been shown to be accurate enough to characterize mesoscale phenomena [Flierl and Robinson, 1977]. It was not until the 1990s that the impact of time-dependant systematic errors on climate applications was recognized. A steady state correction factor was adopted by Sippican after a comprehensive analysis of research-quality CTD and XBT data by Hanawa *et al*. [1995]. This study showed that the manufacturer coefficients in the FRE resulted in depths that were too shallow, producing a cold temperature bias in most of the water column. As a result a stretching factor of 1.0336 was applied to the manufacturer original FRE. Recent studies suggest time-varying biases between XBT and CTD observations [Gouretski and Koltermann, 2007; Wijffels *et al*., 2008]. The implied changes in the FRE exceed the 2% error specified by the manufacturer (Sippican) and are likely to be responsible for spurious decadal signals in global mean heat storage time series [Wijffels *et al*., 2008]. Starting in

2000, the rapidly expanding Argo array [Gould *et al*., 2004] provides global and highly quality controlled ocean temperature and salinity data with CTD accuracy. Nonetheless, XBT profiles currently make up to 25% of the current global temperature profile observations. Therefore, assessing and correcting this bias is critical to monitoring changes of global ocean heat content. Systematic biases between observing systems with disparate quality capabilities, such as Argo and XBTs, can also introduce spurious climatic signals in heat storage as the ratio of the number of observations collected with each platform changes [e.g. Willis 2008]. Temperature profiles obtained from simultaneous deployments of XBTs and CTDs are recommended to continue the assessment of possible regional and temporal changes in the FRE.

6. Simultaneous Observations, the Oleander Project.

Cargo ships provide an excellent platform for obtaining data from other observational platforms along repeated transects. The R/V Oleander is a container vessel that operates the AX32 transect twice a week, between Port Elizabeth, NJ, and Hamilton, Bermuda. Besides deploying XBTs since 1976, the Oleander operates a continuous plankton recorder (CPR) since 1975, an Acoustic Current Doppler Profiler (ADCP) since 1990, a thermosalinograph (TSG) since 1991, and a pCO2 system since 2006. This operation is maintained jointly between the University of Rhode Island, the State University of New York at Stony Brook, and NOAA. The ADCP measures upper ocean currents from the surface to 200-400 m depth depending upon weather, load factor, and backscatter material. This project has provided by far the longest time series of the Gulf Stream. As such it is now in a position to address decadal and longer variability in the structure and variability of currents, including transport. Several factors make this route special. I) It crosses four separate hydrographic regimes, the continental shelf, the Slope Sea, the Gulf Stream, and the northwest Sargasso Sea. Each exhibits quite distinct characteristics. II) It also crosses the Gulf Stream at a location where the meandering is relatively modest making both space and time averaging particularly efficient. As such it provides an excellent monitor of the Gulf Stream transport shortly after it separates from the coast. We have learned much from this. III) The Slope Sea and shelf segments provide an excellent window into the fluxes from the Labrador Sea. Significantly, these fluxes exhibit a factor 2 range in transport variations (on interannual timescales) that appear to be related to the state of the North Atlantic Oscillation. IV) The Sargasso Sea segment also exhibits factor two variations in transport, but these appear to exhibit somewhat faster (interannual) timescales. One can speculate that the Slope Sea fluxes may be driven primarily by changes in the convective state of the Labrador Sea whereas the Sargasso Sea depends more upon variations in wind patterns. Ongoing and near-future research include 1) studies of the horizontal wave number spectrum of velocity, 2) further research into the discovery of a westward flowing jet in the Slope Sea, 3) an inter-comparison of estimated sea level from a (geostrophic) integration of ADCP velocity and sea level from altimetry at cross-over points between the Oleander and two or three satellite track lines, and 4) an update on low-frequency variability and possible trends in transport by the Gulf Stream itself.

7. The Future of the XBT network and of the Ship Of Opportunity Program.

Ten years after OceanObs99, the High Density XBT network continues to increase in value, not only through the growing length of decadal time-series, but also due to integrative relationships with other elements of the ocean observing system:

- One key example is the XBT operation aboard the R/V Oleander along transect AX32, which also has a TSG, CPR, and ADCP installed. Analysis of observations obtained from this operation will be key to understanding the variability of the Gulf Stream.
- The implementation of global broad scale temperature and salinity profiling by the Argo Program underlines a need for complementary high-resolution data in boundary currents, frontal regions, and mesoscale eddies. HD XBT transects together with Argo provide views of the large-scale ocean interior and small-scale features near the boundary, as well as of the relationship of the interior circulation to the boundary-to-boundary transport integrals.
- Fifteen years of continuous global satellite altimetric heights are matched by contemporaneous HD sampling on many transects. The sea surface height (SSH) and the subsurface temperature structure that causes most of the SSH variability are jointly measured and analyzed [Goni and Baringer, 2002].
- Air-sea flux estimates in large ocean areas complement the heat transport estimates from HD transects and the heat storage estimates from Argo.
- Improved capabilities in ocean data assimilation modeling allow these and other datasets to be combined and compared in a dynamically consistent framework.

The XBT network involves the work of many components of the field observations and science international communities. The network presented in Figure 1 supports the recommendations of OceanObs99 and includes several transects that the scientific community has added during the last 10 years. Due to logistical and budgetary constraints some transects may be difficult to carry; however, they are kept as recommendations based on the justifications given by OceanObs99.

The FR transects in the eastern Indian Ocean and the Indonesian region have produced noteworthy scientific insights, and are some of the longest running time series of basin-scale ocean-structure. Never-the-less, many of the global FR transects have not been taken up by the scientific community. The opinion of these authors is that JCOMM should sponsor an analysis to assess the value of FR transects, in particular to determine the optimal sampling frequency and distance between consecutive deployments in these transects. With the full implementation of Argo, the role of the XBTs and its impact on ocean analysis and seasonal forecasts should be re-assessed using numerical modeling and statistical analysis. Regarding real-time ocean analysis, it is important to consider that some redundancy in the observing system is required, especially to assist the automatic quality controlled decisions. For instance, having XBT data in the vicinity of Argo floats can help to detect errors in one or other instruments.

The SOOPIP must continue fulfilling the field operations and data management of the XBT upper ocean thermal requirements established by the Global Climate Observing System (GCOS). The authors of this paper recommend forming an XBT Science Steering Team with members of the scientific and operational communities. This team will be charged with meeting every two years to communicate scientific and operational results, to evaluate the requirements of these two communities, and to maintain a close relationship with SOOPIP for the assessment of the network implementation. The presentation of results in meetings and workshops to emphasize the importance of the XBT network in scientific studies and operational work must continue, particularly to highlight the integration of XBTs with other observational platforms and their impact in the ocean observing system.

Data management will continue to be a critical component of the XBT operations. With the implementation of the new BUFR format, special emphasis must be given to metadata, which can be used, for example, to identify systematic errors in equipments and ships. Transmission of quality controlled data in real-time will continue to be vital for assimilation in climate and weather forecast models. Given the existing different options of data formats and transmission platforms, an evaluation should be made to unify the implementation of full or subsample (inflection points or standard depths) transmissions in real-time. Real-time quality control procedures carried by different institutions will, following the Argo example, be unified. Delayed mode GTSPP data include the full resolution data from XBTs or CTDs from the ships, or fully processed and quality controlled data from the organizations that provided the real time low resolution data to the GTS. The numbers of the delayed-mode measurements added to the archive were 12,737 and 62,252 in 2007 and 2008, respectively.

GTSPP continued to improve its capabilities of serving the GTSPP data for operations and climate research. The GTSPP data sets are available at GTSPP's Web site at http://www.nodc.noaa.gov/GTSPP/. Additionally, delayed-mode XBT data received through the Global Oceanographic Data Archeology and Rescue Program (GODAR) will be processed by the WOD. All delayed-mode XBT data will be available through both the GTSPP database and the WOD (within 90 days of processing).

Technology will continue to play a vital role in the implementation and sustainability of the XBT network. In order to improve the HD operations, collaboration among different institutions should be increased to develop new technology during the upcoming years, including the building and testing of new autolaunchers and acquisition systems that will require less human participation.

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