White Paper #10 – In situ Temperature, Salinity, and Velocity Observations

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1. Establishing Observing System Requirements

The observing system requirements for *in situ* temperature, salinity, and velocity (T,S,V) are set by the space/time scales of phenomena that are to be resolved in applications. The process of observing system design is an iterative one, as improved understanding of the requirements is balanced with new technologies that make more comprehensive observations practical. Observing system design is a compromise between what is required and what is feasible from economical and/or logistical perspectives. Observing system designs relevant to the tropical Pacific Ocean are described for TAO/TRITON (Hayes et al., 1991; Anonymous, 2002), the Argo Program (Argo Steering Team, 1998), the Global Drifter Program (Dohan et al., 2010), and the Expendable Bathy-Thermograph (XBT) Networks (Goni et al., 2010).

Here we consider two classes of observing system requirements for *in situ* T,S,V. The first are for broadscale observations that span the spatial domain of the tropical Pacific Ocean, and are relevant from a climate observing system perspective (sections 1.1, 2, 3.1). The second are for high resolution observations that are needed in specific sub-domains, or for specific processes (sections 1.2 and 3.2). Some observations in this second class will be part of the sustained observations networks, and others are useful to progress the observing system design. These "high-resolution observations" include measurements in the western boundary regions, the equatorial band, and the surface mixed layer. The applications to be served by both classes of observations include basic research, operational modeling and prediction, ocean/climate assessment, and education. These span a broad range of space and time-scales, including mesoscale to basin scale processes, intraseasonal to interannual variability (ENSO research and prediction), decadal fluctuations (including decadal variability of ENSO), and multi-decadal climate change.

1.1 Broadscale T,S,V observations

As a step toward establishing the requirements for broadscale observations, and recognizing that conclusions from other TPOS 2020 White Papers will help in this regard, Table 1.1 and 1.2 provide provisional data requirements for *in situ* T, S, and V, by describing what is needed for different processes to be observed in the tropical Pacific. The separation of broadscale T, S variability into upper ocean and deep ocean components is an artificial one, based on technology and cost limitations. Deep measurements are indispensable for multi-decadal variability, since deep warming plays a significant role in total ocean budgets for energy and sea level (Purkey and Johnson, 2010). Seasonal to interannual variability also extends into the deep ocean, though the importance of deep ocean observations in prediction applications is yet to be tested. Increased cost of full depth profiles relative to upper ocean profiles may impose limits on observed time-scales in the deep ocean.

Table 1.1 – Observing system variable requirements for T, S, and V.

Variable	*Application Area(s)*	*Magnitude of signal*	*Depth Coverage/ Resolution*	*Spatial Coverage/ Resolution*	*Temporal Coverage/ Resolution*
T,S,V	Mesoscale variability	SSS: 0.2 – 0.4 (1)	?	0.25°x0.25°	5 days
T,S	Intraseasonal variability		3 vertical modes	5°x0.5°	5 days
T,S	ENSO research and forecasting	SSS: 0.2 – 0.4 (2)	15m 0 - 500m, higher near sea surface (5)	1.5°x1.5°	1 month
V, SSS	Climate model validation		15m 0 - 500m	Equatorial sites + SPCZ (6)	5 days
T,S, SSS	Climate variability	SSS: 0.2 – 0.5 (3,4)	Sea surface to 2000m	200 km	1 month
T,S	Multi-decadal trends		All water column	500 km	1 month (> 30 years)
T,S,V	LLWBCs and ITF		To 2000m at least or to the bottom ITF passages: >sill depth	10 km ITF: major passages	10 days ITF: 5 days (intraseasonal signals)

Here we do not distinguish between *in situ* temperature and salinity sampling requirements. As with temperature, salinity is an essential climate variable, necessary to estimate density, and especially important in regions including the western Pacific Warm Pool and the shallow thermocline of the eastern tropical Pacific. Salinity is essential for documenting multidecadal change, and useful in forecasting systems (e.g. Hackert et al., 2011).

Table 1.2 – Present observing system designs.

Observing Element	*Variable (s)*	*Random Error*	*Horizontal Coverage/ Resolution*	*Vertical Coverage/ Resolution*	*Temporal Coverage/ Resolution/ Observing Cycle*	*Timeliness*
TAO/TRITON Moored Array	T, S, V		15° longitude 2-3° latitude, 8°S-8°N	~12 depths, 0-500 m	hourly	
Repeat Hydrography	T, S, V and other	T .001 °C S .002	1/2 degree along track; sparse tracks	Top-to-bottom (GO-SHIP); 1-2 dbar resolution	variable	RT: 6 weeks DM: ½ yr
Argo Program	T, S profiles V_{1000}	T .005°C S 0.01	3° x 3° (plus regional enhancements)	0-2000 dbar, 1 - 5 dbar res.	10 days (plus regional enhancements)	RT: 24 hours DM: 1 year
Global Drifter Program	SST, SLP (subset), SSS (subset)	T 0.1°C 0.05°C for subset	5° x 5° (plus regional enhancements)	N/A	Approximately hourly	RT: 24 hours DM: 1/3 yr
VOS Sea Surface Salinity Network	SSS, SST	S .05 (with bucket sampling) T: 0.01	3 km along track; variable across track	0 – 10 m	1-3 month intervals	RT: 24 hours DM: 1 yr
High Resolution XBT Network	T profiles	T 0.2°C Z 2%	10 – 20 km in WBCs	0 – 800 m, 2 m res.	3 month intervals	RT: 24 hours DM: 1/3 yr

Many of the tropical signals have long zonal scales (> 10^6 m) relative to mid-latitude mesoscale variability and longer time scales (> a month), and thus the tropical ocean is easier to observe (in terms of space and timescales) than the higher latitudes. One of the major sources of aliasing is Tropical Instability Waves (TIWs), with 17-30-day period. The small space scales of the TIWs and their complex structures make them quite challenging to observe, and despite their importance for the climate, it is not possible with the present observing system to diagnose adequately their properties. The intraseasonal Kelvin waves (50 to 120-day period), on the other hand, are a realistic and important phenomenon to be observed, perhaps the most demanding tropical phenomenon for broadscale observations. If the observing system requirements for T,S,V are based on these scales of intraseasonal variability, then the larger/slower seasonal-to-interannual signals will also be adequately observed.

As with temperature and salinity, ocean current is an Essential Climate Variable and an Essential Ocean Variable (http://ioc-goos-oopc.org/obs/ecv.php). Broadscale systematic observations of current in the tropical Pacific are provided by a number of networks including the Global Drifter Network, Argo, TAO/TRITON moorings, and TAO/TRITON servicing cruise data. All of these datasets have serious limitations in spatial, depth, and/or temporal sampling. For example, Dohan et al. (2010) noted that the GOOS/GCOS sampling requirement of "one Sea Surface Velocity measurement per month per 5° x 5° box is inadequate for any surface circulation calculation beyond climatology". This objective was inherited from the SST calibration requirement, and does not take into consideration the scales of surface current features. Argo sampling of 1000-m depth velocity provides nearly an order of magnitude more estimates on a yearly basis, but is still inadequate except on long timescales. Mean velocity fields in the tropical Pacific at the sea surface (Maximenko et al., 2008) and at 1000 m (Cravatte et al., 2012) have complex spatial structure. The GOOS/GCOS requirement should be reevaluated for the modern observing system, taking into consideration velocity information indirectly provided by sea surface height, geostrophic shear, and ocean vector winds.

1.2 High resolution T,S,V observations

As noted above, some parts of the ocean, including boundary currents, the Indonesian Throughflow (ITF), the equator, and the surface mixed layer, are not adequately sampled by broadscale observations, and require dedicated observational networks. For the most part, they require a combination of observation types (see section 3.2)

The wind-driven shallow meridional overturning circulation (MOC) is an important component of seasonal to multi-decadal variability in the tropical Pacific mass and heat budgets. While the interior ocean elements of the shallow MOC are observed by the broadscale networks, the low latitude western boundary currents (LLWBCs) that represent an important part of the MOC remain poorly observed by sustained systems. Another critical element of the tropical Pacific mass and heat budgets is the Indo-Pacific exchange of waters via the ITF. Present observational technologies do not permit sampling of the full latitude/longitude/depth/ time structure of the tropical WBC and ITF regions at the required resolution of order 10 km and 10 days. Instead, and in contrast to the areal-mode of sampling addressed in the broadscale networks, boundary current and inter-basin exchange observations are mostly done in line-modes. That is, transects across the WBCs, LLWBCs, and the ITF are obtained by line-mode networks including shipboard hydrography, XBT, gliders, and moorings. These four *in situ* observational types provide a mixture of spatial, depth, and temporal sampling characteristics (see section 3.2). Integrated designs such as Ganachaud et al., (2008) and Hu et al., (2014), merging multiple *in situ* and satellite systems offer promise for sustained observations of the western boundary region. The equator is another important dynamical boundary that requires some enhancement of resolution in T,S,V relative to the off-equator ocean interiors.

In addition to the high horizontal and temporal resolution required for the western boundary region and the ITF, some applications also have requirements for high vertical resolution that are not met by all observational networks. These include studies of ocean mixing and the surface layer, where vertical resolution of 1 dbar or better is required for air-sea exchange estimates with short time-scales that resolve diurnal variability of the T,S stratification. In both applications, high vertical resolution observations may also be needed from broadscale systems and there may be specific regions where high vertical (and temporal) resolution is required.

1.3 Accuracy

Errors in observations of subsurface T(z), S(z) come from both the T,S measurements and the depth or pressure measurements. The vertical temperature gradient averaged over the tropical Pacific ranges from .001°C/dbar at 2000 dbar to 0.07°C/dbar in the shallow thermocline, but may be higher for individual profiles. With pressure errors in shipboard and low-power float and glider CTDs of <1 dbar to 2 dbar (respectively) and temperature errors of <.001°C to .002°C, the pressure errors dominate over temperature errors in the upper ocean for estimating T(z). It is essential to quantify and if possible correct systematic pressure or depth errors in order to ensure consistency in long time-series and consistency between observational networks.

The most demanding application, and hence requirement setting, for T(z), S(z) measurement accuracy is the estimation of long-term climate change. The upper ocean (0-2000 m, volume average) has warmed by .002°C/year (Levitus et al., 2012). Global warming rates decrease with depth in the upper ocean but remain positive over the full water column, with a second maximum of 0.0008 °C/year (Purkey and Johnson, 2010, Figure 2.9c) at 4500 m in the abyss. Combined errors due to spatial coverage and measurement accuracy must be small enough on multi-year time-scales to observe these signals. Wijffels et al. (2008) showed that correction of systematic depth errors in XBT data removed spurious decadal variability in 50-year estimates of global thermosteric sea level and hence ocean heat content.

In conclusion, modern shipboard and low-power float and glider CTDs provide adequate accuracy in T(z) for multi-year estimates of global temperature change, as well as for the larger signals of interannual to decadal variability on a regional basis. A similar conclusion can be drawn for S(z), with the condition that slow drift in salinity is adjusted through Delayed-Mode quality control procedures. The importance of correcting systematic pressure (or depth) errors is underlined, both for historical XBT observations and for modern autonomous pressure sensors.

2. The present sustained networks

2.1 TAO/TRITON moorings

Temperature, salinity, and velocity data are measured by moorings of the TAO/TRITON array [McPhaden et al., 1998] at 11 longitudes across the Pacific from 137°E to 95°W and nominally at latitudes of ±8°, ±5°, ±2°, and the equator (Figure 2.1). Temperature data are generally measured at 11 or 12 depths at all mooring locations between 500 m and the surface, more closely spaced in the vertical in the upper water to resolve the mixed layer and the thermocline, and more coarsely spaced at depth, where thermal gradients and variability are smaller. Salinity is measured from the surface to 500 m at the same depths as temperature on all TRITON moorings, in the western Pacific where barrier layers (Lukas and Lindstrom, 1991) are important. Salinity is measured near the surface from all TAO moorings, and along with subsurface temperature between 120 m and the sea surface at many of the TAO moorings along the equator. Velocity is nominally measured near-surface at all TRITON moorings, and along the equator in the upper few hundred meters at 147°E, 165°E, 170°W, 140°W, and 110°W.

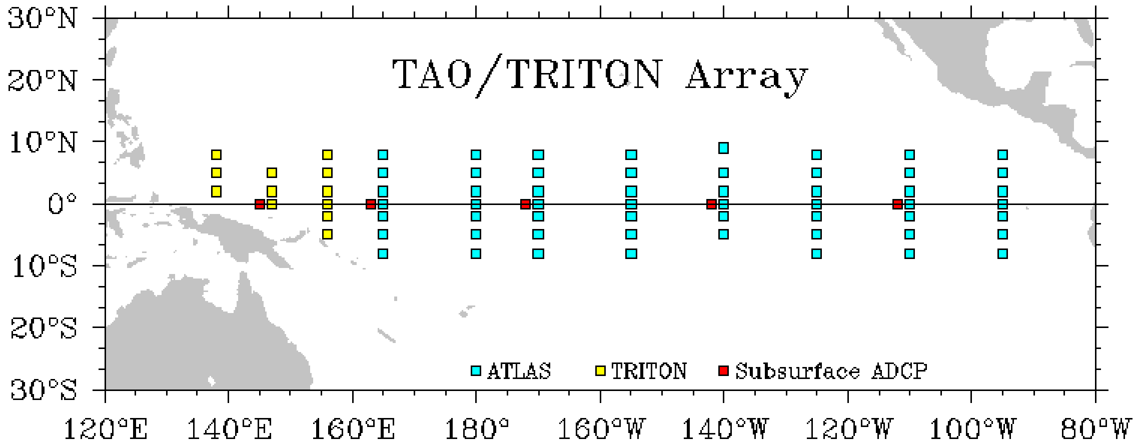

Figure 2.1 – Mooring locations for the TAO/TRITON array.

The vertical spacing of the subsurface moored temperature data is generally adequate to resolve the vertical thermocline structure, but without much redundancy. The lateral spacing of moorings is sufficient to resolve the structure of the thermocline for many timescales, including seasonal and ENSO timescales; it is marginally sufficient for sampling intraseasonal Kelvin waves (Kessler et al., 1996) but greatly insufficient to resolve the small structures and frontal characteristics of the TIWs. Daily temporal resolution is important for avoiding aliasing, although longer intervals (up to five days) between sampling could be sufficient for resolving many phenomena (Kessler et al., 1996). It is worth noting that hourly time series from moorings can also be used for specific process studies, such as surface layer studies (near surface stratification, SST diurnal cycle).

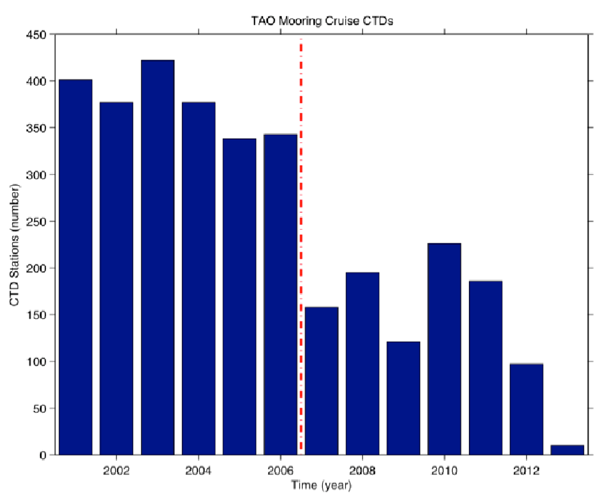

Figure 2.2 – Numbers of CTD casts taken during TAO cruises in each year from 2001-2013 (blue bars). The transition from PMEL to NDBC responsibility for the TAO mooring maintenance cruises (vertical red dashed line) in 2006 is shown. Nominally 366 CTD stations should have been occupied per year, time and equipment allowing.

While the TRITON mooring measurements continue to have a good data return, the TAO moorings have degraded considerably. The TAO array operated at 80–90% data returns from 46–55 moorings in the years just prior to 2006, when maintenance of the array transitioned from NOAA research (PMEL) to Weather Service management operations (NDBC). After the transition was mostly completed at the end of 2006 through 2011 the data return was usually closer to 80% than 90%, with from 45–54 moorings reporting. However, starting in 2012, data return dropped precipitously, falling to around 40% from 31–38 moorings in 2013, as the ship that had been maintaining TAO the array was laid up and not replaced.

TAO/TRITON data, including subsurface temperature, salinity, and velocity data, are used for a broad range of applications, including oceanographic research, climate studies, fisheries studies, and operational and reanalysis products related to oceanography and meteorology. A bibliography of TAO/TRITON research is found at (http://www.pmel.noaa.gov/tao/proj_over/pubs/taopubsr.shtml).

2.2 Repeat hydrography from TAO/TRITON cruises and GO-SHIP

Shipboard temperature, salinity, and pressure (CTD) profiles, and velocity (shipboard ADCP) data have been collected during TAO mooring maintenance cruises along the eight TAO longitudes and similarly along the three TRITON longitudes. Station spacing for TAO CTDs is nominally 1° poleward of ±3° latitude, and 0.5° equatorward of that. CTD data have been collected regularly along TAO longitudes in the eastern equatorial Pacific since 1979, before the pilot moored array was established along 110°W in 1984, with collection generally expanding westward as did the array. Since the array was fully established in 1994, but prior to the transition to operations, CTD transects were often continued north of the northernmost moorings, often to 12°N, to sample the equatorial current system. Data were collected from the surface to 1000 dbar, and deeper when time allowed.

During the six-year period between 2001 and 2006, when PMEL was leading the effort, on average 376 CTD profiles per year were collected during TAO mooring maintenance cruises (Figure 2), more than the nominal target of 366 profiles owing to collection of data north of mooring locations. After the transition to operations and NDBC leadership, data collection fell immediately, with an average of 164 profiles per year collected for the six-year period between 2007 and 2012 (44% of the data collection rate over the previous six years), with no data collected north of the northernmost moorings at each longitude. In 2013, a total of only 10 CTD profiles were collected during TAO maintenance cruises.

Shipboard velocity data were collected using an ADCP, with the first useable data obtained in 1991 (Johnson and Plimpton, 1999). Early ADCP instrumentation profiled only to 300–400 dbar, but an upgrade in 2004 allowed velocity data to be collected to pressures of 600–800 dbar from the NOAA Ship Ka'imimoana, since laid up in 2012. Having recent TAO mooring maintenance cruises on other ships without ADCP instrumentation has sometimes prevented velocity data collection entirely. Additionally, there has been no funding for SADCP data processing within TAO since the 1990s, so the data sets are processed as practicable by J. Hummon and E. Firing at the University of Hawaii.

The shipboard CTD and ADCP data have provided climatological estimates of current velocities, water-properties, and transports across the upper tropical Pacific Ocean, their seasonal cycles (Johnson et al., 2002b), and the effects of ENSO on tropical currents (Johnson et al., 2000). These data are very useful in describing and quantifying narrow features such as the subsurface countercurrents (Rowe et al., 2000). These features are invisible to satellites or surface drifters, and not well resolved by Argo except perhaps in the time-mean (e.g. Taguchi et al., 2012). The shipboard TAO/TRITON data have been widely used for evaluating ocean models and the ocean components of climate models. These data have also provided a divergence-based estimate of equatorial upwelling (Johnson et al., 2001) and direct measurements of the subsurface meridional velocities associated with the tropical cell (Perez et al., 2010).

Additional full-depth repeat hydrographic stations have been collected across the tropics at nominal longitudes of 137°E, 149°E, 165°E, 170°W (in the southern hemisphere only), 150°W, and 110°W at roughly decadal intervals starting with WOCE in the 1990s and now as part of the international GO-SHIP program (http://www.go-ship.org/). Station spacing is nominally 0.5° of latitude, reduced to 0.33° equatorward of ±3°. Full-depth velocity data are collected using a lowered ADCP. These data and others have been used to document large-scale warming of the bottom waters, including the equatorial Pacific (Kouketsu et al., 2011). High quality shipboard CTD data are invaluable for calibrating salinity data from the CTD sensors on Argo floats, which may drift or shift from their pre-deployment calibration after time (Owens and Wong, 2009). Shipboard CTD data must be collected world-wide on a regular basis as a necessary condition for attaining sufficient accuracy of the Argo salinity data set.

In the equatorial-wave guide, full-depth CTD and velocity data are also very useful for studying the propagation of energetic and prominent planetary waves. The propagation of an annual Rossby wave in the equatorial Pacific has been traced across the basin from the surface to 3000 m using temperature profiles (Kessler and McCreary, 1993). Full-depth velocity data collected across the Pacific (Firing et al., 1998) have revealed equatorial deep jets and currents, distinct from the annual signal.

2.3 The Argo Program

The original design of the Argo array (Argo Science Team, 1998) called for a profiling float in each 3° x 3° square, collecting 0-2000 dbar T,S profiles and 1000 dbar velocity estimates every 10 days. Argo achieved its initial global target of 3000 floats in 2007, and the present array includes 3600 active floats. The enormous impact of Argo on subsurface T, S observations in the tropical Pacific (15°S - 15°N) is illustrated in Figure 2.3. The World Ocean Database contains about 37,000 shipboard T, S profiles to at least 1000 m (Figure 2.3), with the distribution of profiles biased toward the coasts and the northern hemisphere. The median number of these profiles per 1° square is 3, and there are many areas with none. In contrast, Argo has so far obtained 150,000 T, S profiles (and trajectories) in the same tropical Pacific domain, with more uniform spatial distribution, and median of 32 profiles per 1° square. Argo coverage is systematic and regular over the domain. The tropical Pacific (15°S - 15°N) contains 4310 1° ocean squares, so the original Argo design requires about 17,500 profiles per year. In 2012 there were 18,455 profiles (Fig 3), and 43% of the 1° squares contained at least 4 profiles that year. Further gains in uniformity of coverage are limited by the availability of float deployment opportunities. Array divergence is an issue for older model floats spending about 10 hours on the sea surface, but much less so for new floats with bidirectional communications, spending about 15 minutes on the sea surface.

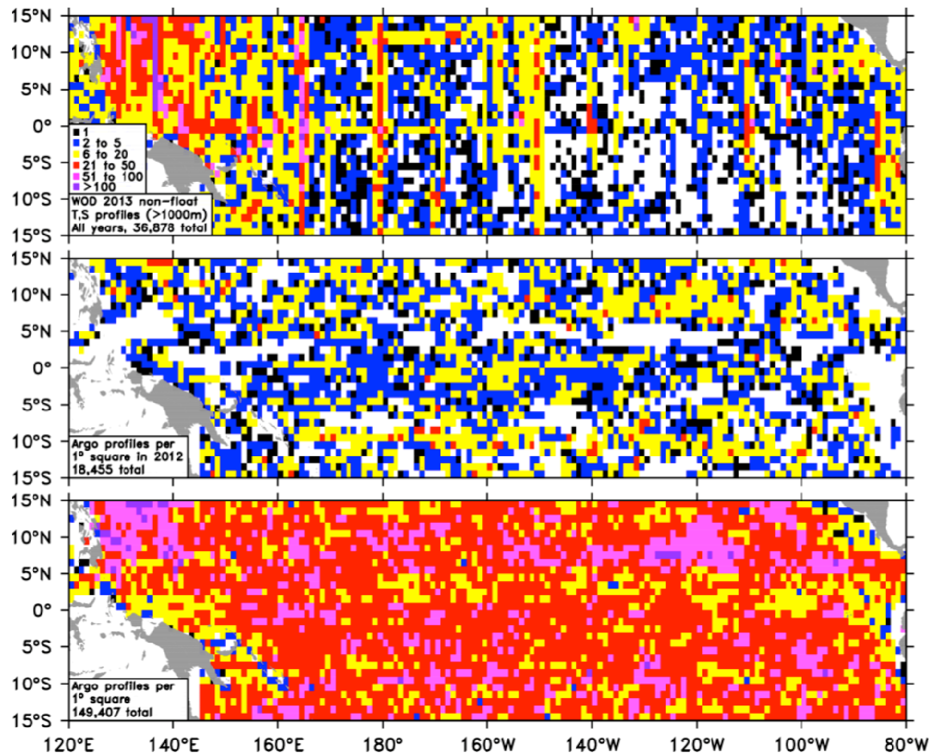

Figure 2.3 – (top) World Ocean Database, all years, non-Argo T,S profiles > 1000 m, per 1° square (36,878 total); (middle) Argo profiles per 1° square in 2012 only (18,455 total); (bottom) Argo profiles per 1° square in the tropical Pacific Ocean (149,407 total).

The OceanObs'09 Conference produced community recommendations for enhancement of the Argo array. These were further discussed at Argo's 4th Science Workshop in 2012, and endorsed by the Argo Steering Team in 2013 (though sustaining the original design of Argo is the top priority). Recommended enhancements impacting the tropical Pacific include denser sampling in western boundary regions and along the equator. A draft map of the revised Argo design is shown in Fig 4. In 2013, a float deployment cruise on RV Kaharoa added 75 floats in the western boundary region of the South Pacific. In late 2013-2014 a deployment of 50 floats along the full length of the Pacific equator will double Argo coverage there. Fig 4 shows the present density of Argo coverage, where 4 floats = 100% represents the "original design" metric for sampling in the 6° x 6° boxes shown in this figure.

Argo's broadscale coverage of the tropical Pacific (Figure 2.4) provides accurate estimates of the mean and annual cycle, for the period 2006 to the present, of T and S in the upper 2000 dbar, and velocity at 1000 dbar. To demonstrate how well Argo captures tropical variability, we use gridded altimetric sea surface height (SSH, AVISO weekly 1/3°) as a well-sampled proxy for steric height. In Figure 2.5, a linear regression of gridded steric height onto SSH in the central equatorial Pacific captures 91% of the variance in the 2006 – 2012 time-series. When this record is separated into low frequency (100-day running mean) and intraseasonal (full minus 100-day running mean) components, the linear regression captures 95% and 79% of the variance respectively. Thus, Argo coverage captures nearly all the low frequency variability (seasonal to interannual) in the tropics. It is less effective for intraseasonal variability, but with the enhanced resolution from the denser sampling described above the estimate of intraseasonal variability will be further improved.

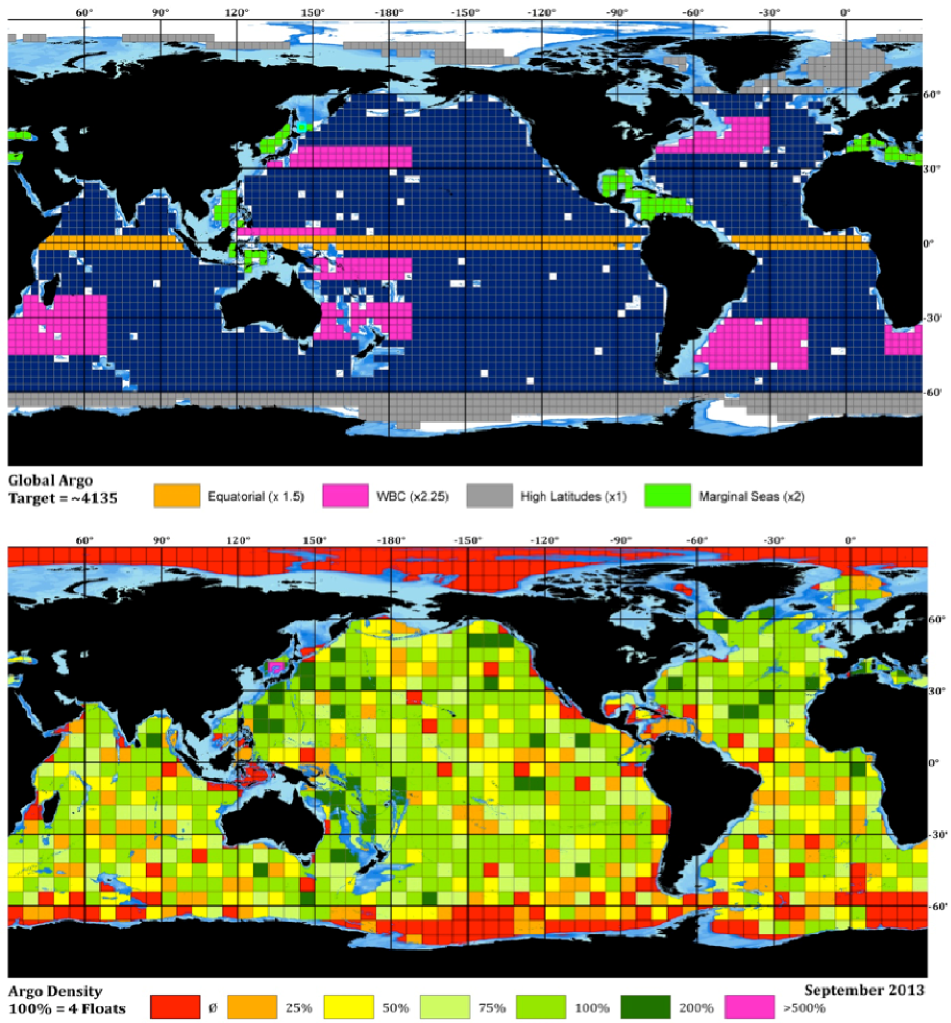

Figure 2.4 – (top) Draft map of recommended regions for enhanced Argo coverage, including western boundary regions and the equatorial band; (bottom) present coverage in 6° x 6° relative to Argo's original design (4 floats = 100%) (Source: Argo information center).

Another community recommendation for Argo is extension of the depth of profiles from the present 2000 dbar limit to full ocean depth profiling. Prototype Deep Argo floats have been deployed using 4000 dbar and 6000 dbar float models. Additional prototype deployments are planned for 2014, including testing of a new ultra-stable 6000 dbar float CTD. Deployment of pilot arrays of Deep Argo floats is expected to begin in 2015. A design for global sampling of

Deep Argo floats will be considered when the capabilities, costs, and support level for the instrument are better known.

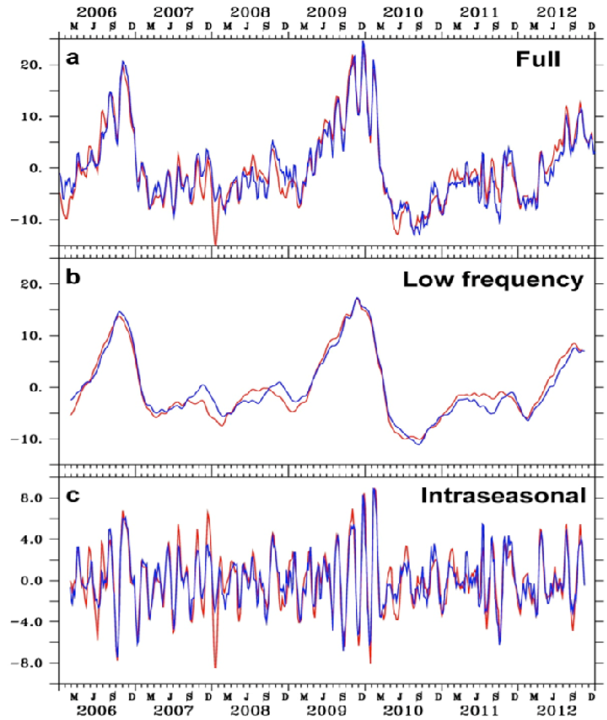

Figure 2.5 – a) SSH (red line, cm, AVISO, after Ducet et al., 2000) averaged over 160° W to 150° W, and 1.5° S to 1.5° N, linear regression of Argo steric height (blue line, cm, 10-day resolution, after Roemmich and Gibson, 2009) onto SSH; b) same but low-pass filtered with 100-day running mean; c) same but using the difference between the full time series and the low pass filtered series.

All Argo data are made publicly available within about 24 hours of collection via the GTS and the internet (2 mirrored Global Data Assembly Centers). A delayed-mode version of the data is available within about a year, including adjustments for salinity drift and pressure error. Trajectory and technical files are also available, and allow the computation of Argo subsurface drift at the parking depth.

2.4 The Global Drifter Program

The network of drogued drifters (at 15-m) in the tropical Pacific is shown in Figure 2.6 (left). Surface velocity from drifters is a valuable source of current information, used as a mean current reference for altimetric height products, and recently in ocean data assimilation using drogued drifters (e.g., Lumpkin and Pazos, 2007). Drifter velocities have been used to quantify monthly variations in equatorial divergence and the surface current response to El Niño events (Lumpkin and Johnson, 2013, see Figure 2.7). Because Figure 2.6 is for the most recent quarter (July-September 2013), it reveals the large gap in the central equatorial Pacific where drifter observations are sparse due to equatorial divergence and lack of reseeding opportunities from TAO servicing cruises. Eastern equatorial observations were collected by some drifters deployed from volunteer ships transiting into the Pacific basin from the Panama Canal, while the westernmost equatorial Pacific was well-sampled by current meters on TRITON moorings. It is clear that a large fraction of the region is not meeting the GOOS/GCOS (1999) requirement (Figure 2.6, right), evaluated here using both drifters and moored current meter sites of TAO/TRITON. The region was better sampled in earlier years (see http://www.aoml.noaa.gov/phod/ soto/gsc/reports.php); returning to coverage meeting the 1999 requirements will require resumption of TAO servicing cruises, or an alternate to repeatedly deploy drifters across a broad swath of the Tropical Pacific.

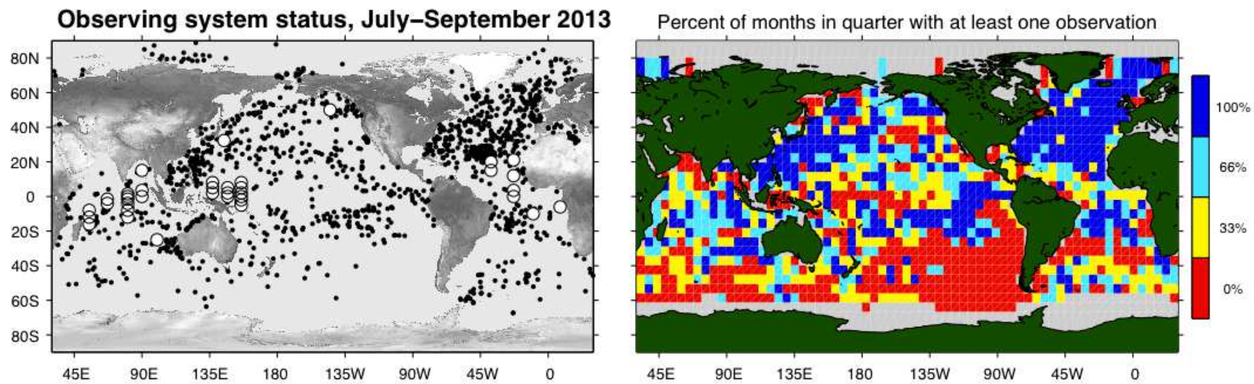

Figure 2.6 – (left) Location of drogued drifters (black dots), and moored near-surface current meter observations (circles) during the quarter July-September 2013; (right) percent of months in the quarter satisfying the GOOS/GCOS requirements for sea surface velocity.

The Eulerian velocity measurements from moorings and Lagrangian measurements from drifters are complementary, but not redundant. With respect to depth, moored acoustic current meters on the Global Tropical Moored Buoy network are placed at 10m depth, while the center of a drifter's drogue is at 15m. More fundamentally, the Eulerian measurements at a mooring are ideal for studies at a site - for example, calculating the impact of heat/salt advection on the mixed layer budget in combination with satellite-based measurements of lateral gradients - while the Lagrangian measurements of a drifter are capable of measuring dispersion, stirring and total derivative (including advective terms) of properties.

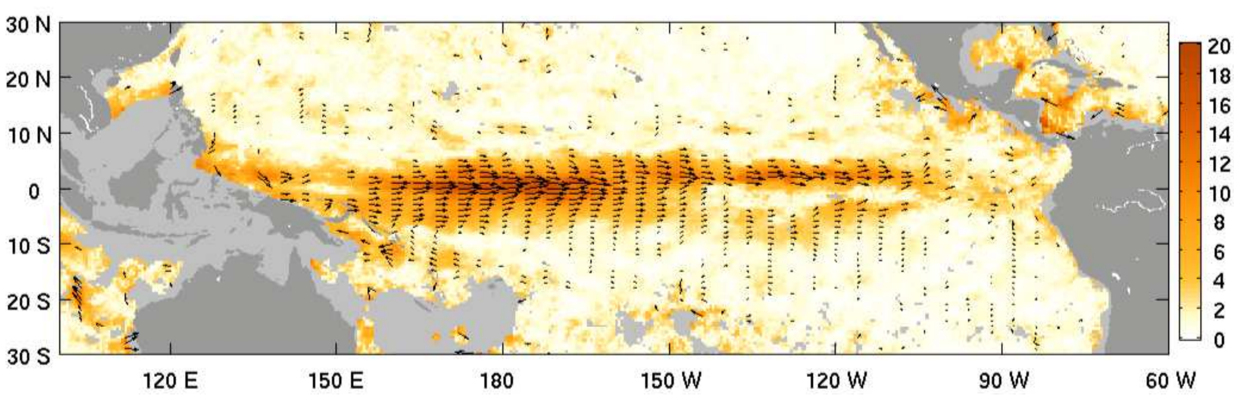

Figure 2.7 – Velocity of drifter-derived currents regressed onto the Southern Oscillation Index (SOI) (colors in cm/s) shown for SOI = -1 (moderate El Niño) with directions (black arrows) indicated for a subset of grid points. Arrows are not shown where their magnitude is not significantly different from zero. Light grey areas have less than 365 drifter days per bin (29 per square degree) (adapted from Lumpkin and Johnson, 2013).

Because they drift, Lagrangian measurements cover a broad area and contribute the vast majority of the 5° x 5° degree bins quantified in maps such as Figure 2.6. The value of Eulerian measurements is underrepresented in such maps, but moored measurements are the most cost-effective way to maintain observations in regions of surface divergence such as the equator. Surface drifters in the tropical oceans are also providers of SST data and are the main source of validation/correction of satellite-based SST products. Some surface drifters also have been equipped to measure surface salinity; these were first used during TOGA-COARE, with large-scale deployments initiated in 2012 in the tropical Atlantic. Prior to the Atlantic SPURS campaign of 2013, this augmentation had been mostly done on an exploratory or dedicated experiment fashion due to the high additional cost of the measurement, and the average time of usable data on any drifter is only 6 months to a year because of salinity sensor fouling and drift. These approximately hourly data can be used to resolve diurnal cycles, explore the response of surface salinity to rainfall and complement other near-surface data.

2.5 The Volunteer Observing Ship Sea Surface Salinity Network

Sea Surface Salinity (SSS) is also an essential climate variable (ECV). Its scientific relevance has been recognized and endorsed in the Oceanobs09 conclusions (Lagerloeff et al., 2010). The Tropical Pacific underway SSS and SST network includes data collected from Voluntary Observing Ships (VOS) and from oceanographic Research Vessels (RV). The VOS data in the tropical Pacific Ocean originated from the French SSS Observation Service (http://www.legos.obs-mip.fr/observations/sss/), dating back to 1969, and presently involves the efforts of international participants through the Global Ocean Surface Underway Data (GOSUD) project (http://www.gosud.org). These *in situ* SSS observations are a critical and quasi-unique source for observing and understanding small scale SSS variability (Figure 2.9). They are also essential for understanding the impact of river discharge on the ocean, evaluating satellite salinity observations (SMOS and Aquarius), and understanding hydrological changes among other physical processes (see http://www.legos.obs-mip.fr/observations/sss/publications/refereed).

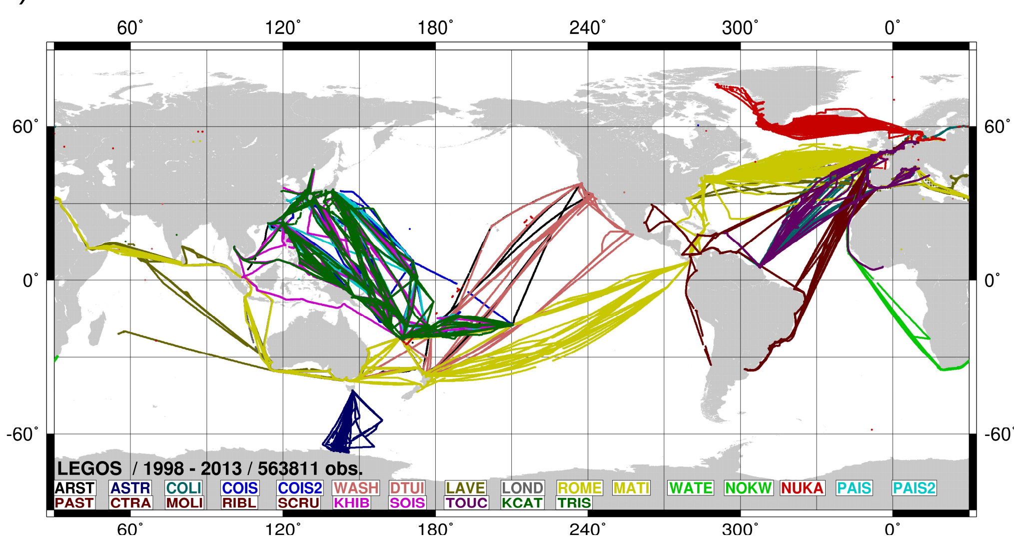

Figure 2.8 – Number of SSS observations per 1° longitude and 1° latitude, expressed in decimal logarithm scale, as obtained from TSG on VOS during 1998-2013.

On average, the contributing ships provide one to three SSS sections per season along a regular track (Figure 2.8). The SSS (& SST) measurements are mainly based on SeaBird SBE-21 TSG instruments located as close as possible to the ship's engine water intake. Most SSS measurements are collected at 15 second intervals, and a 5-minute median value is transmitted in real time, yielding spatial resolution of the order of 1-2 km. The 5-minute real time data are mainly designed to remotely check the on-board TSG systems, as well as for operational oceanography, and their use is not recommended for research purposes since they cannot be properly validated. The real time SSS data received are collected daily via ftp by CORIOLIS, which is the Global Data Acquisition Center for GOSUD.

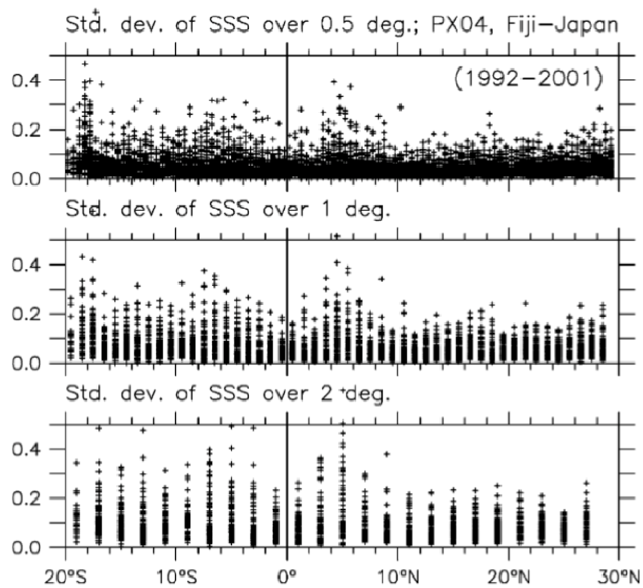

Figure 2.9 – Distribution of the standard deviation values of SSS computed over 0.5°, 1° and 2° latitudes for all 1992-2001 voyages along the Fiji-Japan shipping track (PX04) (from Delcroix et al., 2005).

Delayed mode quality control is made with simultaneous water samples, collocated Argo floats and/or CTD measurements. Once quality controlled, the estimated accuracy of SSS is of order 0.02 pss-78. The delayed mode data are made available from the French SSS Observation Service website, and also archived and made available via the CORIOLIS web site for the international GOSUD network.

2.6 The XBT Networks

The XBT Networks have undergone major evolutions in the past 15 years (Smith et al., 2001, Goni et al., 2010, Figure 2.10) in response to the implementation of the Argo Program and to changes in the commercial shipping industry. The Argo Program has replaced the previous broadscale XBT network, allowing XBT sampling to focus on line-modes while Argo provides the areal coverage. The line-modes include Frequently Repeated XBT (FRX) lines, with 18 or more transects per year at low spatial resolution (typically ~100-150 km), and High Resolution XBT (HRX) lines, with 4 transects per year at high spatial resolution (10-15 km in boundary currents). The shipping industry continues evolving to larger ships travelling on fewer routes, increasing the challenge of maintaining exactly repeating transects on oceanographically important routes. Recognizing that the highest value of HRX transects is in sampling the oceans' boundary currents (and fine-scale features in the ocean interior), the HRX network is re-focusing again, toward boundary current observations, particularly along transects with existing long time-series. The present HRX Network in the Pacific and Indian Oceans (Figure 2.10) is similar in scope to the network in the Atlantic.

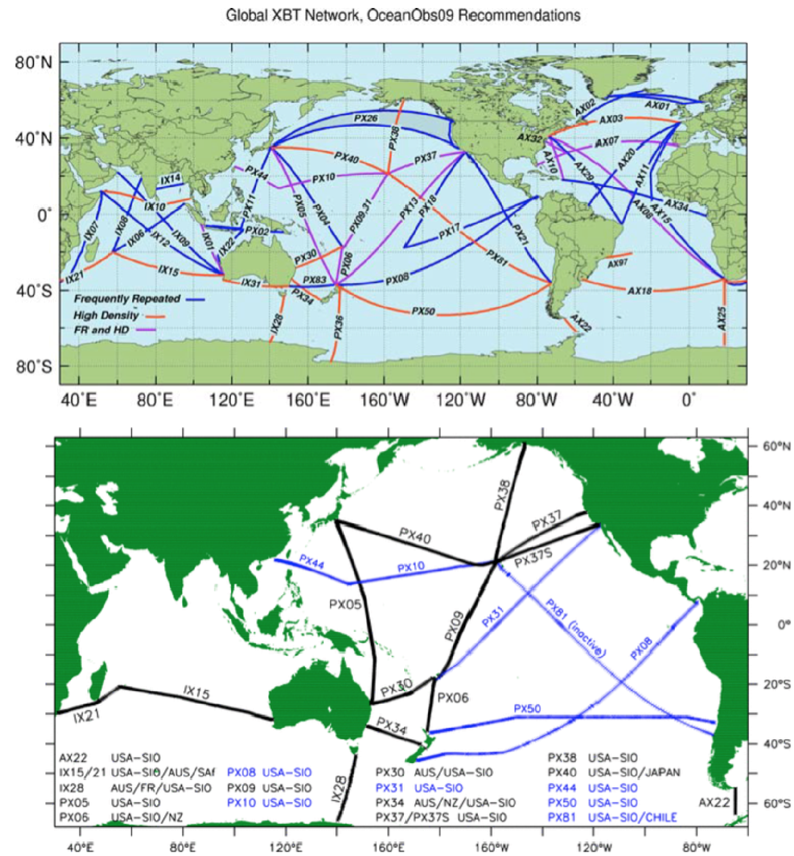

Figure 2.10 – (top) Recommended line-mode sampling from OceanObs'09 (Goni et al., 2010); (bottom) present configuration of the high resolution XBT Network in the Pacific and Indian Ocean. Blue lines are presently inactive, as the network refocuses on boundary current observations.

HRX data are released in near real-time via the GTS and archived by the NODC. As with other line-mode datasets, the primary uses of HRX data are as transects. Transect data are made available on websites of the data providers, but availability in the form of transects (rather than as collections of profiles) through global data centers would increase usage.

3. Integration of networks

3.1 Integration of broadscale networks

The broadscale networks, building on different instrument technologies, have fundamentally different sampling characteristics. It is these contrasts in spatial and temporal coverage and resolution that can be exploited for integrating the total information content of the datasets. For example, the moored observations of the TAO/TRITON network provide high temporal resolution at widely-spaced fixed point locations, while the Argo array provides denser spatial coverage at lower frequency and at varying locations. Each of these datasets can reveal what is missed by the other – the moorings documenting temporal aliasing by Argo's 10-day cycling, and the floats showing the spatial patterns missed by the moored array. In the same way, Eulerian surface velocity measurements from moorings and Lagrangian velocity measurements from drifters are complementary, as noted in section 2.4. Drifters provide a broader spatial coverage, and moorings allow continuous time series, especially at the equator where drifters diverge.

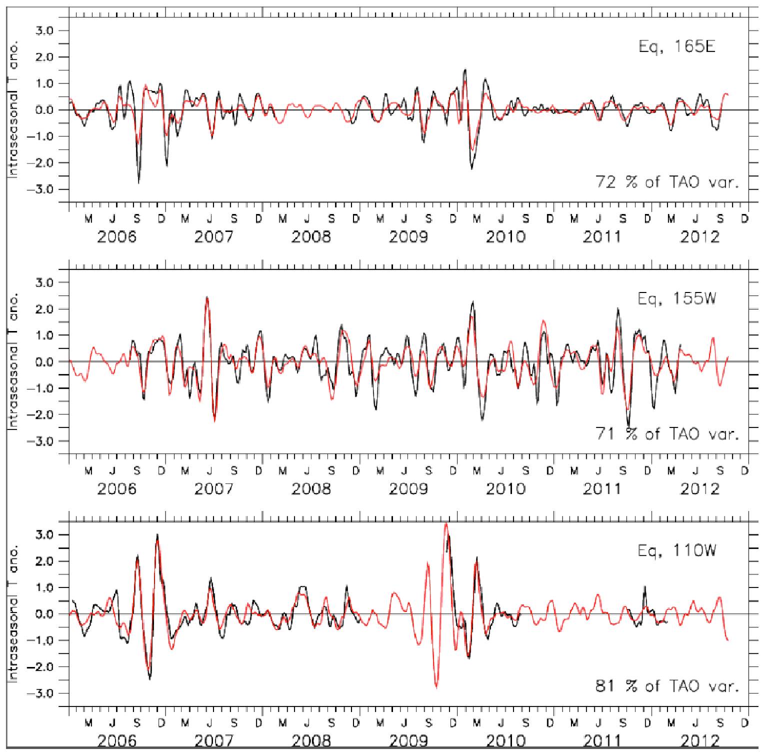

Figure 2.11 – TAO time series (black), 10 day-running mean, of 100 m temperature at 3 equatorial locations, compared with Argo data interpolated to the same locations (red).

An important first step in system integration is analysis of the individual datasets and comparisons to quantify their respective biases. For some variables, such as SSS, it can be challenging to mix data from different instruments, with different depth, accuracy, and coverage, without biasing the resulting mixed product. In that case, careful simultaneous data comparisons (VOS TSG and concurrent Argo profiles or CTDs) are needed to validate the different datasets, evaluate their differences and possibly readjust the data to finally obtain a consistent long interannual SSS gridded product (Delcroix et al., 2011). Similarly, producing climate-quality Argo salinity data requires comparisons with shipboard CTD data that have been carefully calibrated to international standards (Wong et al., 2003). Another important step is analysis of the individual datasets and comparisons to quantify their respective limitations. In Figure 11, Argo temperature at 100 m depth is interpolated to mooring locations in the western, central, and eastern equatorial Pacific. The Argo records are then filtered with a 100-day running mean to separate low frequency and intraseasonal variability, for comparison with moored data at the same locations. For the low frequency variability, which has large spatial scales, Argo captures over 90% of the variance of the moored records. The intraseasonal signals are more challenging due to their shorter spatial scales (Kessler et al., 1996), and Figure 2.11 shows that Argo captures only 71 – 81% of the intraseasonal variance in the moored time-series.

The key to observing system integration is accurate knowledge of the spatial and temporal statistics (autocovariance) of T,S,V in the tropical Pacific (e.g. Meyers et al., 1991, Kessler et al, 1996), as well as the covariances linking T,S,V with related observations. The interannual timescale of ENSO, and its strong decadal modulations, require multi-decadal time series for estimating covariances. At present, remaining uncertainties in the statistics result in substantial differences in the estimated optimal interpolation (OI) mapping errors. In Figure 2.12, OI error maps are displayed for the TAO/TRITON array, with 2.12a using the functional fit to the autocovariance from Roemmich and Gilson (2009).

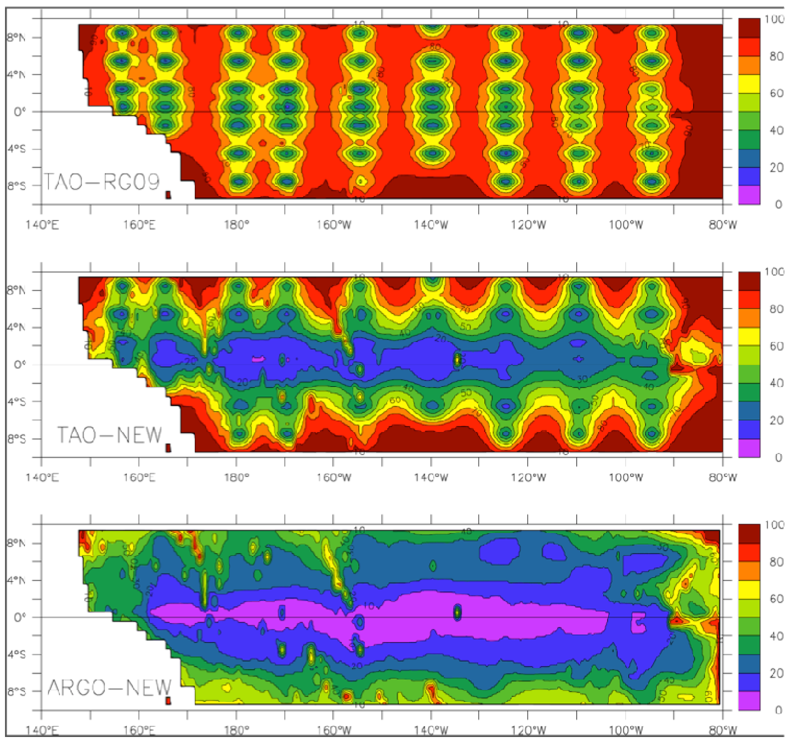

Figure 2.12 – Optimal interpolation fractional mapping error variance (%) for a) TAO/TRITON spatial coverage, using the Roemmich and Gilson (2009) covariance, b) TAO/TRITON coverage, using the Gasparin et al. (2014) covariance, and for c) Argo spatial coverage using Gasparin et al. (2014) covariance.

This representation and similar ones by Ducet et al. (2000) and Kessler et al. (1996) decay more rapidly (meridionally and zonally) than the present (extended) Argo dataset indicates, and so they produce larger errors than indicated by comparisons with independent datasets that are withheld from the mapping (e.g. Figures 2.5 and 2.11). Figure 2.12b is based on a functional covariance with realistic scales based on Argo data (Gasparin et al., 2014, in preparation), and the same is used to estimate mapping errors based on Argo coverage in Figure 2.12c. A general characteristic of OI is that small differences in the covariance function can make large differences in estimated errors (Figure 2.12). OI error maps are very sensitive to details of the covariance. Thus, for applications requiring accurate error estimates, such as array design and evaluation, extensive datasets are needed to develop accurate representation of the covariance function, and independent (withheld) data are important for confirming that error estimates are realistic.

All of the broadscale *in situ* networks are sparsely sampled, but their resolution can be augmented through integration with satellite observations. The key synergies in the ocean observing system (e.g., Roemmich et al, 2010), are those linking subsurface T,S,V with SSH and with air-sea exchanges of momentum, heat, and freshwater (e.g. Willis et al., 2003; Willis and Fu, 2008; Ridgway and Dunn, 2010; Rio et al., 2011). Variability in SSH is dominated by subsurface density (mainly temperature), and the global, systematic character of satellite altimetry makes it powerful in combination with subsurface datasets to amplify their space/time resolution. One approach (e.g., Guinehut et al., 2012) has been to project SSH and SST variability onto subsurface T(z) anomalies as a first guess of the time-varying field, then using temperature profile data for an OI estimate based on this first guess. A more general approach would utilize all datasets containing T(z) information, which might include wind stress and air-sea heat flux as well as SSH and T(z) profiles. As long as accurate estimates are available of the covariances of these data with T(z), improved estimation of the vertical and horizontal structure of temperature or density fields can be made. S(z) is more weakly correlated with SSH than T(z), and so resulting estimates are strongly dependent on the existence of salinity profile data. A further step in dataset integration is through the use of ocean data assimilation models. The same statistics of the underlying datasets are required, but in addition, dynamical consistency imposed by the model can add information and value to the statistically based analyses. Both the multivariate approach (*in situ* plus satellite combinations) and ocean data assimilation modeling are powerful tools for amplifying the scope/domain/resolution of broadscale datasets. However, caution is warranted, and independent datasets should be maintained that are sufficient to assess the skill and limitations of these powerful methods.

3.2 Integration of networks observing the WBC systems and ITF

The LLWBCs - the New Guinea Coastal Undercurrent (NGCU) and the Mindanao Current - are essential elements of the shallow MOC supplying waters of low to mid-latitude origin to the equatorial Pacific. On ENSO timescales, the LLWBCs have been shown to partially compensate the interior transport variability, and are thus key components for the recharge/discharge of the equatorial warm water volume. As such, their properties, and their transport of mass, heat and freshwater should be monitored continuously in order to complete the Tropical Pacific Observing System. In the same way, the poleward western boundary currents - East Australian Current (EAC) and Kuroshio - that influence the climate of the mid-latitudes are not well resolved. The variability of the South Equatorial Current (SEC) and North Equatorial Current bifurcations into equatorward LLWBCs and poleward WBCs are poorly observed. Flowing close to the coast, and concentrated in narrow jets, the boundary currents are not adequately sampled by the broadscale networks, and require dedicated observations, and integration across networks.

Currently, observations of the western boundary regions are being made in the context of specific programs, and some for limited time periods. The feasibility of sustained regional observing systems is being tested and demonstrated. Contributions to Western Boundary Current observations include full-depth moorings, repeated gliders surveys, end-point moorings and Pressure Inverted Echo Sounders (PIES, Send et al., 2010), HR-XBT transects, and shipboard repeat hydrography.

- Moorings are useful for monitoring transports, temperature and salinity of boundary currents in locations where they are sufficiently confined by the bathymetry for adequate sampling by a small number of fixed point measurements. Along coasts where the offshore extent of the boundary current is not well defined, or in larger straits, a line of moorings can be deployed, and integrated with regional or basin-wide observations.
- Underwater gliders (Davis et al., 2002) provide, at a moderate cost, repeated transects of the WBCs, measuring T, S along their route, and vertically integrated velocity. They are able to cross strong currents, albeit with irregular routing, and to sample close to the coast and in shallow waters. Their sampling (typically of 4-km horizontal resolution and to 1000-m depth) resolves the small scales of the boundary currents. Their slow speed and irregular paths pose issues for analyses.
- End-point moorings and PIES: density profiles spanning the boundary current and bottom pressure sensors can provide fluctuations of horizontal integrals of mass transport over large distances, but do not resolve the internal structure.
- HR XBT repeated transects can also help to sample the boundary currents. In some locations such as the EAC off Brisbane a combination of HR XBT, gliders, and moorings, sampled along a common transect, can overcome the limitations of the individual networks.

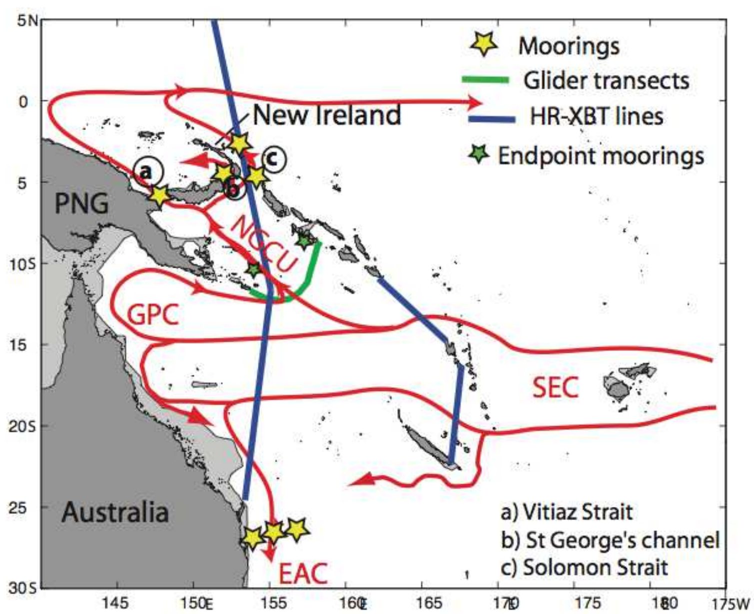

Figure 2.13 – Schematic view of the thermocline circulation in the Southwestern Pacific, and observational network in the context of the SPICE project (NGCU = New Guinea Coastal Undercurrent; GPC = Gulf of Papua Current; SEC = South Equatorial Current; EAC = East Australian Current).

A combination of these approaches can meet the challenges posed by the complex western boundary regions (Ganachaud et al., 2013, Figure 2.13). Integrated planning such as this will define the regional sustained observing system. Here we describe observations in the southwest tropical Pacific and ITF. Those in the northwest tropical Pacific are described briefly below and in greater detail in a separate contribution (Hu et al., 2014, Figure 2.14).

Presently, the circulation of the southwest Pacific is being observed (Figure 2.13) using moored arrays, glider transects, HR-XBT transects, and hydrography. Moorings equipped with ADCP, current meters, and T, S sensors were deployed in July/August 2012 in Vitiaz Strait, Solomon Strait and St. George's channel) (Eldin et al., 2013) to sample the flow exiting the Solomon Sea toward the equator. Two additional moorings, designed for duration of 1.5 years, have been deployed east of New Ireland to sample the New Ireland Coastal Undercurrent. Since 2007, gliders have measured the transport across the south entrance of the Solomon Sea, with four to eight crossings annually (Davis et al., 2012). The Solomon Sea glider transects are supplemented by Pressure Inverted Echo Sounders across the entrance of the Solomon Sea to provide horizontal integrals of mass transport at high temporal resolution.

To monitor the EAC transport, moorings were deployed in April 2012 off Brisbane (Fig 13, http://www.imos.org.au/), close to HR-XBT Line PX30. HR-XBT transects also allow a monitoring of the SEC transport and of its bifurcation. The SECARGO line samples the transport between New Caledonia and Vanuatu (Maes et al., 2011). Line PX05 extends northward from Brisbane, crossing the East Australian Current (EAC), the SEC, the Gulf of Papua Current (GPC), and the central Solomon Sea, exiting very close to New Ireland at 5°S. Thus, the net transport across this line is equal to the combined flow through Vitiaz Strait and St George's Channel (Fig 13). Other HRX lines in the tropical Pacific domain sample the upstream Kuroshio (PX44), and zonal flows in the central tropical Pacific (PX09).

Another critical element of the tropical Pacific circulation is the leakage of mostly warm and fresh tropical waters from the Pacific to the Indian Ocean through the Indonesian seas via the ITF. The ITF forms the only low latitude oceanic pathway for the global thermohaline circulation, and plays important roles in the interbasin transfer of heat and freshwater. Intense mixing occurs in the Indonesian seas, leading to water mass transformations. The interbasin exchange consists of several filaments that pass through the complex bathymetry of the Indonesian seas, making measurement of the total ITF logistically challenging. The observing system for the ITF has included moored arrays, frequently repeated XBT lines, pressure recorders, and repeat hydrography. There are no Argo floats in interior Indonesian seas presently, but this is technically feasible and important for global interannual heat and freshwater content.

During the 2004-2006 INSTANT program, a moored array measured the major components of the full-depth ITF simultaneously through the inflow passage Makassar Strait (Gordon et al., 2008), and the exit passages of Lombok, Ombai and Timor (Sprintall et al., 2009). Since INSTANT, ITF transport measurements have mostly continued (with a gap from August 2011 – August 2013) in Makassar Strait through a single ADCP and current meter mooring, designed to resolve the full-depth transport, with recovery and redeployment planned in 2015. The deepest outflow passages of Ombai and Timor are instrumented by an array of moorings along a Jason altimeter track that crosses the Australian Northwest Shelf. This includes 3 moorings on the shelf, 3 tall moorings at the eastern end of the Timor trench and a single mooring in Ombai

Strait, all resolving full depth velocity, with discrete temperature and salinity sensors and PIES. These moorings were deployed in 2011, with next planned turn-around in mid-2014, and data are available through the IMOS web data portal (http://imos.aodn.org.au/imos/). Other discrete moorings in individual passage are planned for deployment by the Chinese Academy of Sciences (2013-2018).

Three frequently repeated XBT transects represent the longest continuous time series of temperature profiles and geostrophic velocity/transport within the Indonesian Seas (Wijffels et al., 2008). The IX1 line spans between southwestern Australia and Java while PX2 crosses the lower Banda Sea to the shelf break off northwest Australia. Both these transects were established around 1984. Line IX22 was established a few years later, and samples from the Australian northwest shelf across the Savu Sea and the Banda Sea. All three lines are subject to strong ageostrophic internal tide variability.

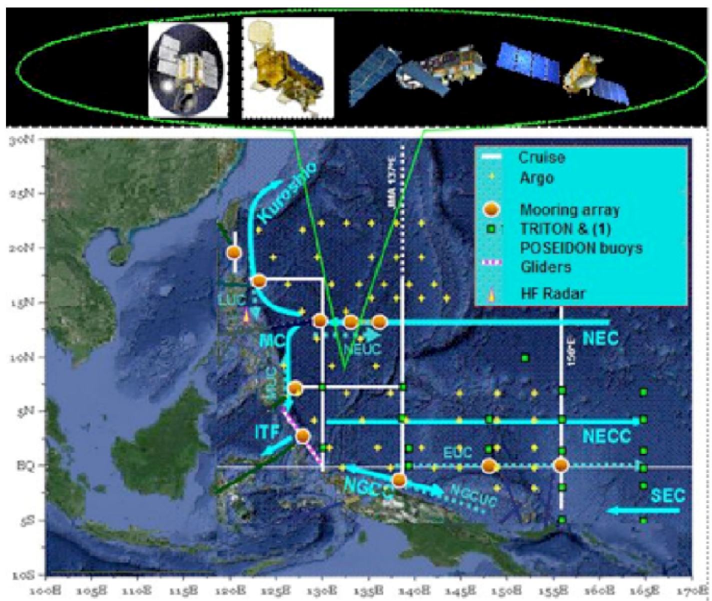

Figure 2.14 – Schematic view of the circulation in the Northwestern Pacific, and observational network in the context of the NPOCE Project (Hu et al., 2014).

The western tropical North Pacific is a critical crossroads for ocean circulation, linking the equatorial and subtropical North Pacific, communicating with the southern hemisphere along a range of density levels and with the Indian Ocean via the ITF. The Mindanao Current is the primary pathway for subtropical North Pacific waters to reach equatorial latitudes. This low latitude WBC system may play significant roles in ENSO variability through source waters for equatorial upwelling in the shallow MOC, and in the process of tropical Warm Water Volume recharge and discharge. However, understanding of these roles is limited by a lack of observations. In order to mitigate this limitation, the NPOCE observational framework (Hu et al., 2014 and Figure 2.14) is focused on the North Equatorial Current bifurcation into the poleward Kuroshio and the equatorward Mindanao Current (and ITF). Repeat hydrographic transects and moored arrays along historically sampled lines (8°N, 18°N, and 130°E) are the central elements for observing each of these three circulation components. In addition, glider transects, and enhanced areal sampling by Argo floats and surface drifters are included on a regional basis.

4. Gaps

4.1 Sustained WBC region and ITF observations

As discussed in Section 3.2, there are short-term (a few years) observations in the boundary current regions and the ITF, but the primary multi-decadal sustained observations of these currents are provided by the XBT networks. These transects have serious limitations (temporal resolution, 0-800 m in depth, no salinity or velocity). The WBCs usually extend deep, and integrate forcing over the entire basin; their variability thus includes a wide range of phenomena, and requires a frequent sampling. Moreover, their narrow width (around 100 km) also requires a sampling at 25 km resolution or higher. Sustained observing systems in these regions should be designed and implemented for full-depth coverage of T, S, V in order to resolve volume, heat, and freshwater transport variations on timescales of a season and longer. These systems are essential to close the basin-wide Meridional Overturning Circulations, including western boundary currents and interior circulations, and the low latitude Indo-Pacific exchange. Sustained systems may include glider and HR-XBT transects, repeat hydrography, Argo floats, moorings, and satellite altimetry. They would require international collaboration to share costs, and in particular ship time.

A key conclusion from the community consensus on sustained ocean observations, including both OceanObs'99 (Smith et al., 2001) and OceanObs'09 (Fisher et al., 2010), was that sustained boundary current and inter-basin exchange observations are primary missing elements of the global ocean observing system. Work already underway in the western boundary region of the tropical Pacific in the context of NPOCE and SPICE programs is a valuable starting point for the global system. However, there is not yet a plan for sustaining observations currently funded by time-limited national projects. In the ITF region, observations are being maintained by individual programs in the Makassar inflow and Lesser Sunda Island outflow passages. Additional observations are needed in the northeastern Indonesian seas to record the primary inflow from the Southern Hemisphere that provides the major salt contribution to the ITF.

4.2 Deep ocean broadscale observations

The present Argo array spans only the upper ocean, 0 – 2000 m, due to technology limitations. Broadscale observations of the deep ocean are obtained by the GO-SHIP repeat hydrography program, but these transects are overly sparse spatially and temporally. Research and operational drivers for systematic observations of the deep ocean include closure of global and regional budgets for heat, freshwater, and sea level. Away from the equatorial waveguide and from the boundary currents, deep ocean interest is mainly focused on decadal and longer timescales, including the mean circulation and its variability. However, there remains much to understand concerning the intraseasonal, seasonal and interannual variability of the deep ocean components, including ENSO-related equatorial waves.

Prototype Deep Argo floats have been deployed demonstrating the capability of profiling to 6000 m. Low power ultra-stable CTDs are also under development to meet accuracy requirements for deep ocean temperature and salinity decadal variability and multi-decadal change. Design and implementation of a deep component of Argo is needed, based on the practical capabilities and endurance of deep floats and CTDs as well as on the sampling requirements for decadal variability.

4.3 Near-equatorial velocity

Present direct velocity observations (surface drifters, Argo float trajectories, equatorial moored ADCP, TAO/TRITON cruise shipboard ADCP) do not resolve the near-equatorial meridional and zonal structure and temporal variability of the mixed-layer (ageostrophic + geostrophic) velocity. Equatorial upwelling – the horizontal divergence of the surface layer transport – is a critical process for the tropical Pacific Observing System. It is a dominant term of the cold tongue heat budget at ENSO timescales, and thus should be monitored. Conventional observational techniques have not proven adequate for this objective, except perhaps in estimating the long-term mean, for which consistent credible estimates have been provided using different techniques (Bryden and Brady, 1985; Johnson et al. 2001). Estimates of upwelling variability require dedicated process studies, such as mooring deployments at higher latitudinal resolution than the present TAO array (e.g., Weisberg and Qiao, 2000), in order to determine the requirements for sustained observations.

4.4 Mixed-layer variability in relation to air-sea fluxes

Near-surface observations are needed of the vertical structure of T, S, whose changes must balance the air-sea exchanges of heat and freshwater. Balances of air-sea flux and ocean storage are important on timescales as short as diurnal. On longer timescales the advection of heat and freshwater anomalies also becomes increasingly important in the budgets. Due to the large range of spatial and temporal scales involved, a combination of *in situ* observational systems may be required, potentially including moorings, Argo floats, and gliders in addition to high resolution satellite observations. For the observing system, at any location where fixed-point time series of air-sea fluxes of heat and freshwater are maintained, there should be subsurface T(z) and S(z) observations that resolve diurnal variability and that have vertical resolution in the surface layer sufficient for calculation of heat and freshwater storage. In addition, the observing system requires measurements of the velocity and of the horizontal gradients of T(z) and S(z), in order to evaluate the advective terms in the heat and freshwater balance.

4.5 Eastern boundary regions

Eastern boundary regions, including the far eastern equatorial band, the Peru-Chile upwelling systems, and the Costa Rica dome, are not adequately sampled by the current in situ networks (compare Figures 2.1, 2.4, 2.6). Moreover, they are regions of strong eddy activity and of small-scale processes that complicate their monitoring. Yet, they are regions of great societal and ecological importance. Understanding how equatorial signals (such as ENSO) are transmitted by way of equatorial and coastal Kelvin waves to the eastern boundary is fundamental in regard to their climatic impacts. Important physical phenomena remain poorly documented: among them vertical advection in the far east during ENSO events, the fate of the equatorial undercurrent and Tsuchiya jets and the Peru upwelling waters sources (Takahashi et al., 2014, WP8). The role of eddies in redistributing biological properties would also require dedicated observations. Observational networks should be tested in the region to improve our understanding of these issues and help to define which regional sustained observing system would be needed.

5. Data and information systems

In the global broadscale *in situ* networks, data and information systems have developed around the individual networks, including TAO/TRITON (http://www.pmel.noaa.gov/tao/index.shtml), the Argo Program (http:/www.argo.net), repeat hydrography (Go-Ship: http://www.go-ship.org/), the HR XBT program (http://www-hrx.ucsd.edu), the Global Drifter Program (GDP, http://www.aoml.noaa.gov/phod/dac), and the VOS SSS data (http://www.legos.obs-mip.fr/observations/sss/). The data management teams of these networks deserve credit for high data quality and ease in data delivery. A persistent issue is the chronic underfunding of the data management systems. Where there are identified issues of interoperability, effort has been expended to resolve these. For example, Delayed-Mode Quality Control of Argo profile data requires timely access (6-12 months) to the best quality shipboard hydrographic data. Progress on this issue is ongoing. Most of the broadscale networks have open data policies that ensure public availability of all data in near real-time (TAO/TRITON, Argo, GDP, VOS). Open data policies are a key element in the sustained observations programs, allowing maximum utilization of the data in both research and operational reanalysis and forecasting applications.

There is a gap in the distribution and availability of SSS, SST, and ADCP data collected underway during scientific cruises. Most research vessels steaming in the TPO are fitted with TSG and SADCP instruments which, in principle, can collect SSS, SST and velocity data while in transit between port calls or hydrographic stations. These data, once compiled, can be usefully used to provide velocity or SSS climatologies (e.g. Johnson et al., 2002b; Dutrieux et al., 2009; Cravatte et al., 2011). The data acquisition and quality control procedures are however not systematic. There is clearly a need to centralize all underway SST and SSS data in a unique data portal, and international efforts should be made to collect, validate and archive all underway SSS and SST data derived from RVs. Similarly, SADCP data need a careful processing before being made publicly available (through the Joint Archive for Shipboard ADCP, http://ilikai.soest.hawaii.edu/sadcp/), and this data processing is currently unfunded.

In addition to the basic datasets, the data management systems also provide a range of data products, some of which have noteworthy utility. Widely disseminated data products in the tropical Pacific include Niño sea surface temperature indices, thermocline depth, and warm water volume. These products and indices have been developed to characterize the ENSO state of the tropical Pacific and for testing ideas about the genesis and evolution of ENSO episodes. Other noteworthy data products are the gridded global versions of Argo temperature and salinity data (http://www.argo.ucsd.edu/Gridded_fields.html), gridded SSS products from various datasets (http://www.legos.obs-mip.fr/observations/sss/) and the drifter velocity climatology (Lumpkin and Johnson, 2013; http://www.aoml.noaa.gov/phod/dac/ dac_meanvel.php). These gridded datasets have greatly increased the accessibility of *in situ* data for research and education applications, and have amplified the number of research publications that utilize the data. Other useful delayed-time products are the global datasets of subsurface Argo velocities (YoMaHa05 from Yoshinari et al., 2006; and ANDRO from Ollitrault and Rannou, 2013). The Argo Program is in the process of upgrading trajectory and technical files, to make estimates of drift velocity more accurate and accessible to users, but manpower limitations in data management are a limiting factor.

The high-resolution datasets collected in the western boundary, ITF, and equatorial regions are, for the most part, readily available from the data providers. However, there is a need to fully document and co-ordinate the consistency of data quality control, since these data sets are generally maintained and made available by individual investigators. As the suite of high-resolution sustained observations is not fully defined, so the data systems are still under development. Argo's data management system has been a model emulated by other observational networks, and inclusive data management systems have been developed or are emerging for fixed point moored time-series data (Ocean Sites), repeat hydrography, and ocean gliders. In total, the data management systems provide access to the high-resolution datasets. However, if the primary utility of the high-resolution data is for regional observations including multiple data types, then consideration is needed for joint distribution of all datasets needed for a particular boundary current or other high-resolution phenomenon. In addition, data products that integrate the high-resolution datasets are needed.

6. Potential tradeoffs for a more efficient observing system

In Section 3 it was noted that *in situ* T,S,V observations can be augmented by related satellite datasets, including wind stress, sea surface height, sea surface temperature and sea surface salinity, and through constraints imposed by ocean dynamics in data assimilation modeling. Here we offer a cautionary note with regard to these powerful approaches. If the observing system now appears to have redundancies, in most cases these are complementary datasets that are essential for independent checking and assessment of system performance. An example was provided (Figure 2.11) to show the skill level in mapping intraseasonal variability along the equator from broadscale Argo data. Moored time-series data were essential to validate mapping accuracy, due to the level of uncertainty in formal error estimates. Equivalently one might use Argo data to assess the accuracy of spatial maps based on TAO/TRITON measurements. The Tropical Pacific Observing System has a long, well-documented history of combining fixed-point time series with broadscale variable-location observations, beginning with the XBT networks. The latter approach was improved by implementation of the Argo Program, providing higher resolution than was possible with broadscale VOS XBT profiling, as well as much greater measurement accuracy and depth range, and the addition of salinity profiles and 1000 m trajectories. While Argo has increased the capabilities of the TPOS overall, it has not obviated the need for fixed-point time series measurements. In the future, the need for economies may diminish the use of large ships in support of the TPOS, but it should not upset the scientific balance of contrasting observational approaches. Greater efficiency is to be found not in reduced observations but in new technologies and improved cost effectiveness. Sustaining multi-decadal time series observations, and particularly in the equatorial region, should be a given for TPOS 2020.

References

Anonymous (2002): International Workshop for Review of the Global Tropical Moored Buoy Network. Workshop Report GCOS No. 77, GOOS No. 122, ICPO No., Seattle WA, June 2002.

Argo Science Team (1998): On the design and implementation of Argo - An initial plan for a global array of profiling floats. International CLIVAR Project Office Report 21, GODAE Report 5. GODAE International Project Office, Melbourne, Australia, 32 pp.

Brandt, P., Funk, A., Hormann, V., Dengler, M., Greatbatch, R.J., and Toole, J.M. (2011): Interannual atmospheric variability forced by the deep equatorial Atlantic Ocean, Nature, 473(7348), pp. 497-U237, (doi:10.1038/nature10013).

Bryden, H. L., and Brady, E.C. (1985): Diagnostic model of the three- dimensional circulation in the upper equatorial Pacific Ocean. J. Phys. Oceanogr., 15, pp. 1255–1273.

Cravatte, S., Ganachaud, A., Duong, Q., Kessler, W.S., Eldin, G., and Dutrieux, P. (2011): Observed circulation in the Solomon Sea from SADCP data, Prog. Oceanogr, 88(1–4), pp. 116–130.

Cravatte, S., Kessler, W., and Marin, F. (2012): Intermediate zonal jets in the tropical Pacific Ocean observed by Argo floats. Journal of Physical Oceanography, 42, pp. 1475–1485. (doi: 10.1175/JPO-D-11-0206.1).

Davis, R., Kessler, W., and Sherman, J. (2012): Gliders measure Western Boundary Current transport from the South Pacific to the Equator. Journal of physical Oceanography 42, 2001–2013. (doi: 10.1175/JPO-D-12-022.1).

Delcroix, T., McPhaden, M., Dessier, A., and Y. Gouriou, Y. (2005): Time and space scales for sea surface salinity in the tropical oceans. Deep Sea. Res. 52/5, pp. 787-813, (doi:10.1016/j.dsr.2004.11.012).

Delcroix, T., Alory, G., Cravatte, S., Correge, T., and McPhaden, M.J. (2011): A gridded sea surface salinity data set for the tropical Pacific with sample applications (1950-2008). Deep-Sea Research Part I-Oceanographic Research Papers, 58, pp. 38-48.

Dohan, K., and Co-Authors (2010): "Measuring the Global Ocean Surface Circulation with Satellite and In Situ Observations" in *Proceedings of OceanObs'09: Sustained Ocean Observations and Information for Society (Vol. 2),* Venice, Italy, 21-25 September 2009, Hall, J., Harrison, D.E. & Stammer, D., Eds., ESA Publication WPP-306, doi:10.5270/OceanObs09.cwp.23

Ducet, N., Le Traon, P.Y., and Reverdin, G. (2000): Global high resolution mapping of ocean circulation from TOPEX/Poseidon and ERS-1 and -2. Journal of Geophysical Research 105 (C8), pp. 19477–19498.

Dutrieux, P. (2009): Tropical Western Pacific Currents and the Origin of Intraseasonal Variability Below the Thermocline, PhD in Oceanography, University of Hawaii, Honolulu, Hawaii, USA.

Eldin, G., Ganachaud, A., Cravatte, S., and Jeandel, C. (2013): Pandora cruise provides an unprecedented description of the solomon sea, CLIVAR Newsletter Exchanges, 61 (18), pp. 24–25.

Firing, E., Wijffels, S.E., and Hacker, P. (1998): Equatorial subthermocline currents across the Pacific, Journal of Geophysical Research-Oceans, 103(C10), 21413-21423, (doi:10.1029/98jc01944).

Ganachaud et al. (2013): Ocean circulation of the Southwest Pacific: new insights from the Southwest Pacific Ocean and Climate Experiment (SPICE), submitted to JGR.

Ganachaud, A., and Co-Authors (2008): Southwest Pacific Ocean Circulation and Climate Experiment (SPICE)—Part II. Implementation Plan. International CLIVAR Project Office, CLIVAR Publication Series No. 133, NOAA OAR Special Report, NOAA/OAR/PMEL, Seattle,WA, 36 pp.

Goni, G., and Co-Authors (2010): "The Ship of Opportunity Program" in Proceedings of OceanObs’09: Sustained Ocean Observations and Information for Society (Vol. 2), Venice, Italy, 21-25 September 2009, Hall, J., Harrison, D.E. & Stammer, D., Eds., ESA Publication WPP-306, (doi:10.5270/OceanObs09.cwp.35).

Gordon, A.L., Sprintall, J., Van Aken, H.M., Susanto, D., Wijffels, S., Molcard, R., Ffield, A., Pranowo, W., and Wirasantosa, S. (2010): The Indonesian Throughflow during 2004-2006 as observed by the INSTANT program, Dynamics of Atmosphere and Oceans, 50, pp. 115-128.

Gordon, A., and Co-Authors (2010): "Interocean Exchange of Thermocline Water: Indonesian Throughflow; "Tassie" Leakage; Agulhas Leakage" in Proceedings of OceanObs’09: Sustained Ocean Observations and Information for Society (Vol. 2), Venice, Italy, 21-25 September 2009, Hall, J., Harrison, D.E. & Stammer, D., Eds., ESA Publication WPP-306, (doi:10.5270/OceanObs09.cwp.37).

Guinehut, S., A. L. Dhomps, G. Larnicol, and P. Y. Le Traon, 2012: High resolution 3-D temperature and salinity fields derived from in situ and satellite observations, Ocean Sci., 8(5), 845-857, http://www.ocean-sci.net/8/845/2012/

Hackert, E., Ballabrera-Poy, J., Busalacchi, A.J., Zhang, R.H., and Murtugudde, R. (2011): Impact of sea surface salinity assimilation on coupled forecasts in the tropical Pacific, J. Geophys. Res., 116, C05009, (doi:10.1029/2010JC006708).

Hayes, S.P., Mangum, L.J., Picaut, J., Sumi, A., and Takeuchi, K. (1991): TOGA TAO: A moored array for real-time measurements in the tropical Pacific Ocean. Bulletin of the American *Meteorological Society*, 72, pp. 339-347.

Hu, D., Wu, L., Wang, F., Yuan, D., Chen, D., Tian, J., Chen, Z., and Hu, S. (2014): On the Northwestern Pacific Ocean Circulation and Climate. White Paper, TPOS 2020 Workshop, La Jolla California, January 2014.

Johnson, E. S., and Plimpton, P.E. (1999): TOGA/TAO shipboard ADCP data report, 1991–1995. NOAA Data Report ERL PMEL-67, NTIS: PB2002-101766, NOAA/Pacific Marine Environmental Laboratory, 23 pp.

Johnson, G. C., Kunze, E., McTaggart, K.E., and Moore, D.W. (2002a): Temporal and spatial structure of the equatorial deep jets in the Pacific Ocean, Journal of Physical Oceanography, 32(12), pp. 3396-3407, (doi:10.1175/1520-0485(2002)032<3396:tassot>2.0.co;2).

Johnson, G. C., McPhaden, M.J., and Firing, E. (2001): Equatorial Pacific ocean horizontal velocity, divergence, and upwelling, Journal of Physical Oceanography, 31(3), pp. 839-849, (doi:10.1175/1520-0485(2001)031<0839:epohvd>2.0.co;2).

Johnson, G. C., McPhaden, M.J., Rowe, G.D., and McTaggart, K.E. (2000): Upper equatorial Pacific Ocean current and salinity variability during the 1996-1998 El Niño-La Niña cycle, Journal of Geophysical Research-Oceans, 105(C1), pp. 1037-1053, (doi:10.1029/1999jc900280).

Johnson, G. C., Sloyan, B.M., Kessler, W.S., and McTaggart, K.E. (2002b): Direct measurements of upper ocean currents and water properties across the tropical Pacific during the 1990s, Progress in Oceanography, 52(1), pp. 31-61, (doi:10.1016/s0079-6611(02)00021-6).

Johnson, G. C., and Zhang, D.X. (2003): Structure of the Atlantic Ocean equatorial deep jets, Journal of Physical Oceanography, 33(3), pp. 600-609, (doi:10.1175/1520-0485(2003)033<0600:sotaoe>2.0.co;2).

Kessler, W. S., and J. P. McCreary (1993), The annual wind-driven Rossby-wave in the subthermocline equatorial Pacific, Journal of Physical Oceanography, 23(6), pp. 1192-1207, (doi:10.1175/1520-0485(1993)023<1192:tawdrw>2.0.co;2).

Kessler, W., Spillane, M., McPhaden, M., and Harrison, D.E. (1996): Scales of variability in the equatorial Pacific inferred from the Tropical Atmosphere-Ocean buoy array. Journal of Climate, 9, pp. 2999 – 3024.

Kouketsu, S., et al. (2011): Deep ocean heat content changes estimated from observation and reanalysis product and their influence on sea level change, Journal of Geophysical Research-Oceans, 116, 16, (doi:C0301210.1029/2010jc006464).

Lagerloef, G., and Co-Authors (2010): "Resolving the Global Surface Salinity Field and Variations by Blending Satellite and In Situ Observations" in Proceedings of OceanObs'09: Sustained Ocean Observations and Information for Society (Vol. 2), Venice, Italy, 21-25 September 2009, Hall, J., Harrison, D.E. & Stammer, D., Eds., ESA Publication WPP-306, (doi:10.5270/OceanObs09.cwp.51).

Levitus, S., and Co-Authors (2012): World ocean heat content and thermosteric sea level change (0–2000 m), 1955–2010, *Geophysical Research Letters,* 39, L10603, (doi:10.1029/2012GL051106).

Lukas, R., and Lindstrom, E. (1991): The mixed layer of the western equatorial Pacific ocean, Journal of Geophysical Research-Oceans, 96, pp. 3343-3357.

Lumpkin, R., and Pazos, M., (2007): Measuring surface currents with Surface Velocity Program drifters: the instrument, its data, and some recent results. Chapter 2 of "Lagrangian Analysis and Prediction of Coastal and Ocean Dynamics", ed. A. Griffa, A. D. Kirwan, A. Mariano, T. Ozgokmen and T. Rossby, Cambridge University Press.

Lumpkin, R., and Johnson, G. (2013): Global Ocean Surface Velocities from Drifters: Mean, Variance, ENSO Response, and Seasonal Cycle. *J.* Geophys. Res.-Oceans, 118(6), pp. 2992-3006.

Maximenko, N. A., Melnichenko, O.V., Niiler, P.P., and Sasaki, H. (2008): Stationary mesoscale jet-like features in the ocean, *Geophysical Research Letters*, 35, L08603, (doi:10.1029/2008GL033267).

McPhaden, M. J., et al. (1998), The tropical ocean global atmosphere observing system: A decade of progress, Journal of Geophysical Research-Oceans, 103(C7), 14169-14240, (doi:10.1029/97jc02906).

Meyers, G., Phillips, H., Smith, N., and Sprintall, J. (1991): Space and time scales for optimal interpolation of temperature – Tropical Pacific Ocean. Progress in Oceanography, 28, pp. 189 – 218.

Ollitrault, M., and Rannou, J.R. (2013): ANDRO: An Argo-Based Deep Displacement Dataset. Journal Of Atmospheric And Oceanic Technology, 30(4), pp. 759-788. (doi:10.1175/JTECH-D-12-00073.1).

Owens, W. B., and Wong, A.P.S. (2009): An improved calibration method for the drift of the conductivity sensor on autonomous CTD profiling floats by theta-S climatology, Deep-Sea Research Part I-Oceanographic Research Papers, 56(3), pp. 450-457, (doi:10.1016/j.dsr.2008.09.008).

Perez, R. C., Cronin, M.F., and Kessler, W.S. (2010): Tropical Cells and a Secondary Circulation near the Northern Front of the Equatorial Pacific Cold Tongue, Journal of Physical Oceanography, 40(9), pp. 2091-2106, (doi:10.1175/2010jpo4366.1).

Purkey, S. G., and Johnson, G. C. (2010): Warming of global abyssal and deep Southern Ocean waters between the 1990s and 2000s: Contributions to global heat and sea level rise budgets. Journal of Climate 23, pp. 6336-6351.

Rio, M. H., Guinehut, S., and Larnicol, G. (2011): New CNES-CLS09 global mean dynamic topography computed from the combination of GRACE data, altimetry, and in situ measurements, J. Geophys. Res., 116, C07018, (doi:10.1029/2010JC006505).

Roemmich, D., and Co-Authors (2010): "Integrating the Ocean Observing System: Mobile Platforms" in Proceedings of OceanObs'09: Sustained Ocean Observations and Information for Society (Vol. 1), Venice, Italy, 21-25 September 2009, Hall, J., Harrison, D.E. & Stammer, D., Eds., ESA Publication WPP-306, (doi:10.5270/OceanObs09.pp.33).

Roemmich, D., and Gilson, J. (2009): The 2004–2008 mean and annual cycle of temperature, salinity, and steric height in the global ocean from the Argo Program. Progress in Oceanography, (doi:10.1016/j.pocean.2009.03.004).

Rowe, G. D., Firing, E., and Johnson, G.C. (2000): Pacific equatorial subsurface countercurrent velocity, transport, and potential vorticity, Journal of Physical Oceanography, 30(6), pp. 1172-1187, (doi:10.1175/1520-0485(2000)030<1172:pescvt>2.0.co;2).

Sabine, C. L., et al. (2004): The oceanic sink for anthropogenic CO_2, Science, 305(5682), pp. 367-371, doi:10.1126/science.1097403.

Smith, N., and Co-Authors (2001): The upper ocean thermal network. From: Observing the Oceans in the 21st Century, C. Koblinsky and N. Smith, Eds, Bureau of Meteorology, Melbourne, pp 259-284.

Sprintall, J., Wijffels, S.E., Molcard, R., and Jaya, I. (2009): Direct estimates of the Indonesian Throughflow entering the Indian Ocean, Journal of Geophysical Research 114, C07001, (doi: 10.1029/2008JC005257).

Taguchi, B., Furue, R., Komori, N., Kuwano-Yoshida, A., Nonaka, M., Sasaki, H., and Ohfuchi, W. (2012): Deep oceanic zonal jets constrained by fine-scale wind stress curls in the South Pacific Ocean: A high-resolution coupled GCM study, Geophys. Res. Lett., 39, L08602, (doi:10.1029/2012GL051248).

Tanhua, T., Waugh, D.W., and Bullister, J.L. (2013): Estimating changes in ocean ventilation from early 1990s CFC-12 and late 2000s SF_6 measurements, Geophysical Research Letters, 40(5), pp. 927-932, (doi:10.1002/grl.50251).

Weisberg, R. H., and Qiao, L. (2000): Equatorial upwelling in the central Pacific estimated from moored velocity profilers. J. Phys. Oceanogr., 30, pp. 105–124.

Wijffels, S. E., Willis, J., Domingues, C.M., Barker, P., White, N.J., Gronell, A., Ridgway, K., and Church, J.A. (2008): Changing expendable bathythermograph fall rates and their impact on estimates of thermosteric sea level rise, Journal of Climate, 21, pp. 5657– 5672.

Wijffels, S.E., Meyers, G., and Godfrey, J.S. (2008): A 20-yr average of the Indonesian Throughflow: Regional Currents and the interbasin exchange, Journal of Physical Oceanography, 38, pp. 1965-1978.

Willis, J.K., Roemmich, D., and Cornuelle, B. (2003): Combining altimetric height with broadscale profile data to estimate steric height, heat storage, subsurface temperature and sea-surface temperature variability, J. Geophys. Res., 108,(C9) 3292, (doi:10.1029/2002JC001755).

Willis, J. K., and Fu, L.L. (2008): Combining altimeter and subsurface float data to estimate the time-averaged circulation in the upper ocean, J. Geophys. Res., 113, C12017, (doi:10.1029/2007JC004690).

Wong, A. P. S., Johnson, G.C., and Owens, W.B. (2003): Delayed-mode calibration of autonomous CTD profiling float salinity data by theta-S climatology, J. Atmos. Oceanic Technol,, 20, pp. 308–318, (doi:10.1175/1520-0426(2003)020<0308:DMCOAC>2.0.CO;2).

Yoshinari, H., Maximenko, N.A., and Hacker, P.W. (2006): YoMaHa'05—Velocity data assessed from trajectories of Argo floats at parking level and at the sea surface. IPRC Tech. Note 4, 16 pp.

Zilberman, N., Roemmich, D., and Gille, S. (2013): The mean and the time variability of the shallow Meridional Overturning Circulation in the tropical South Pacific Ocean. Journal of Climate, 26, pp. 4069 – 4087.