Assessment of the Upper-Ocean Observing System in the Equatorial Pacific: The Role of Argo in Resolving Intraseasonal to Interannual Variability*

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(Manuscript received 23 November 2014, in final form 28 May 2015)

ABSTRACT

Using more than 10 years of Argo temperature and salinity profiles (2004–14), a new optimal interpolation (OI) of the upper ocean in the equatorial Pacific is presented. Following Roemmich and Gilson's procedures, which were formulated for describing monthly large-scale anomalies, here every 5 days anomaly fields are constructed with improvements in the OI spatial covariance function and by including the time domain. The comparison of Argo maps with independent observations, from the TAO/TRITON array, and with satellite sea surface height (SSH), demonstrates that Argo is able to represent around 70%–80% of the variance at intraseasonal time scales (periods of 20–100 days) and more than 90% of the variance for the seasonal-to-longer-term variability. The RMS difference between Argo and TAO/TRITON temperatures is lower than 1°C and is around 1.5 cm when the Argo steric height is compared to SSH. This study also assesses the efficacy of different observing system components and combinations, such as SSH, TAO/TRITON, and Argo, for estimating subsurface temperature. Salinity investigations demonstrate its critical importance for density near the surface in the western Pacific. Objective error estimates from the OI are used to evaluate different sampling strategies, such as the recent deployment of 41 Argo floats along the Pacific equator. Argo's high spatial resolution compared with that of the moored array makes it better suited for studying spatial patterns of variability and propagation on intraseasonal and longer periods, but it is less well suited for studying variability on periods shorter than 20 days at point locations. This work is a step toward better utilization of existing datasets, including Argo, and toward redesigning the Tropical Pacific Observing System.

1. Introduction

Observing and modeling the tropical Pacific are crucial for describing and predicting the evolution of the El Niño–Southern Oscillation (ENSO) phenomena in addition to tropical, regional-to-global scale, decadal variability, and multidecadal change. The interannual variability of the ocean–atmosphere system is associated with a combination of processes having different spatial and temporal scales (Kessler and Kleeman 2000; Roundy

and Frank 2004; Eisenman et al. 2005), and an observing system has been established in the tropical Pacific to improve description, understanding, and prediction of basinwide atmospheric and oceanic variability. Initiated by the Tropical Ocean and Global Atmosphere (TOGA) program, Tropical Atmosphere Ocean/Triangle Trans-Ocean Buoy Network (TAO/TRITON) moorings are the foundation of this observing system and have provided multidecadal oceanic and atmospheric fields (Hayes et al. 1991; McPhaden et al. 1998). Significant progress has been made in the recognition of ENSO characteristics, and in modeling and forecasting of ENSO phenomena through these observations, which have continued to evolve with the development of new technologies, including satellite and in situ systems, during the last two decades.

The Tropical Pacific Observing System (TPOS) was originally designed to study large-scale interannual variability by measuring oceanographic and meteorological variables at the air–sea interface, and temperature down through the oceanic thermocline, while recognizing the

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* Supplemental information related to this paper is available at the Journals Online website: <http://dx.doi.org/10.1175/JTECH-D-14-00218.s1>.

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DOI: 10.1175/JTECH-D-14-00218.1

potential importance of smaller-scale and higher-frequency fluctuations (McPhaden et al. 1998). Satellites have greater spatial resolution than the tropical moored array at the ocean surface, and the Argo program extends the depth range and horizontal resolution of subsurface observations and includes measurements of salinity (Freeland et al. 2010). Originally the 10-day temporal and $3^\circ \times 3^\circ$ spatial sampling scheme of the Argo program was designed and implemented to provide global coverage of the upper ocean, 0–2000 dbar, on broad spatial scales and on time scales of months and longer (Roemmich et al. 1998).

In the tropical Pacific, important variability occurs on diurnal, intraseasonal, seasonal, and longer time scales. Intraseasonal variability in the equatorial waveguide is thought to participate in the evolution of ENSO episodes through eastward-propagating Kelvin waves driven by westerly wind events (WWEs; Harrison and Vecchi 1997; McPhaden et al. 1998; Lengaigne et al. 2003; Eisenman et al. 2005). These propagating thermocline features have a zonal extent of several thousand kilometers, but they also contain shorter-scale variability that is not well resolved by the 15° longitude spacing of TAO/TRITON moorings. However, the relative strengths of TAO/TRITON include velocity measurements that add significant discriminating power and unique information about intraseasonal Kelvin wave dynamics (Kutsuwada and McPhaden 2002). In addition, TAO/TRITON surface fluxes and velocity in combination with temperature can inform the diagnosis of mixed layer temperature variability on intraseasonal time scales (McPhaden 2002).

Several studies have investigated how various observing system components contribute to improving model-based ocean analyses and reanalyses or to the skill of seasonal forecasts (Smith and Haines 2009; Balmaseda and Anderson 2009). These studies highlight the dominant impacts of the TAO/TRITON array in comparison to Argo and altimetry on seasonal forecast skills, but they focus on time periods before 2006, when the Argo array had not yet achieved its designed configuration. Other studies are underway now to determine how various datasets constrain ocean analyses. In addition to data coverage, the length of time series, including altimetry, TAO/TRITON, and Argo, can also affect their impact on data syntheses.

Here, we focus on Argo impacts in the tropical Pacific observing system. Early models of Argo floats, spending about 12 h on the sea surface during each cycle, were carried out of the equatorial band by surface layer Ekman divergence. Newer models, using Iridium communications, mitigate this problem with 15-min surface periods, enabling much longer residence times on the

equator (see supplemental Fig. 1). To test Argo's ability to observe intraseasonal variability, the existing Argo array was enhanced by 41 floats deployed along the equator from 100°W to 160°E from January to March 2014. The new deployments are expected to improve the description of intraseasonal variability and to be valuable in modeling and data assimilation for the full range of intraseasonal and longer-term variability in the equatorial Pacific Ocean.

Several estimates of subsurface properties using Argo data are made for the global ocean, using optimal interpolation (OI) of the irregularly spaced data onto evenly spaced grids (Bretherton et al. 1976). This technique requires accurate representation of the space–time covariance of the data (e.g., Roemmich and Gilson 2009, hereafter RG09). In the equatorial Pacific, estimates of the decorrelation scales have been made based on TAO/TRITON moorings (Kessler et al. 1996), expendable bathythermograph (XBT) transects (Meyers et al. 1991), and more recently with early years of Argo float data (RG09). In the present work, a more accurate data covariance function and noise-to-signal ratio are provided based on more than 10 years of Argo data, and the impacts of the improved OI are illustrated.

Aims of this work are to assess the improved estimation of subsurface properties in the equatorial Pacific in three ways:

- (i) by considering a more accurate data covariance function that includes temporal in addition to spatial scales, based on a decade of Argo data
- (ii) by assessing the OI estimation errors in Argo-based maps using independent data sources (TAO/TRITON and altimetry)
- (iii) by evaluating different observational elements and combinations in the TPOS and specific sampling enhancements, such as the recent equatorial Pacific Argo float deployments in early 2014

Finally, this technical investigation is followed by a description of the recent intraseasonal variability of the upper ocean observed by Argo along the equator. As a component of an observing system, Argo's capability to represent upper-oceanic conditions from intraseasonal to interannual time scales constitutes one of the main objectives of this work.

The paper is organized as follows. Datasets are presented in section 2. A description of sample and modeled covariances and the noise-to-signal ratio used in the OI are shown in section 3. In section 4, subsurface property estimations and their associated errors are assessed by comparing with independent datasets. Then, the eastward propagation of features including oceanic Kelvin waves is investigated in section 5. Conclusions are provided in section 6.

FIG. 1. Locations of temperature profiles from XBT, CTD, TAO/TRITON moorings, and Argo floats in the equatorial Pacific for (top) March 1998 and (middle) March 2012 (*World Ocean Atlas 2013*; Locarnini et al. 2013). (bottom) Locations of temperature profiles for Argo floats for March 2014.

2. Data

a. Temperature/salinity from Argo floats

Temperature and salinity profiles from Argo floats were acquired from the Argo Global Data Assembly Center (GDAC) websites (www.coriolis.eu.org/; www.usgodae.org/argo/) in late 2014 for the period January 2004 to August 2014. For this period, more than 110 200 profiles were found in the equatorial Pacific between 10°S and 10°N. Low-quality profiles (equivalent to 20% of the total profiles) are excluded after several quality control tests were performed as described in RG09. More than 90% of the floats have a cycling period of 10 days, while the others are cycling every 7 days (including the 41 floats deployed in the beginning of 2014). The shorter cycle time is expected to improve the estimation of intraseasonal variability (Roemmich et al. 1998), and these new-generation floats [Sounding Oceanographic Lagrangian Observer-II (SOLO-II)] have a short surface time of 15 min (due to the Iridium two-way communications) and reduced equatorial divergence. The Argo program has made a major contribution to subsurface ocean sampling in the tropical Pacific (Fig. 1). By 2006 Argo was close to its objective of $3^{\circ} \times 3^{\circ}$ spacing in the equatorial Pacific (about 300 profiles every 10 days; 10°S–10°N; Fig. 2). The higher-resolution sampling following the deployments of

the 41 Argo floats along the equator can be seen in Fig. 1, totaling around 120 profiles every 10 days between 2°S and 2°N (Fig. 2).

b. Temperature/salinity from TAO/TRITON moorings

Implemented as part of the TOGA program (McPhaden et al. 1998), the TAO/TRITON array in the equatorial Pacific is used here primarily for comparison as an independent dataset. This array of around 70 subsurface moorings (~0–500 m) was designed with a spatial resolution of 2° – 3° in latitude and 15° – 20° in longitude, located between 8°S and 8°N. At the mooring sites a variety of atmospheric and oceanic measurements provide high-temporal resolution with sampling intervals as short as minutes for some variables (Milburn et al. 1996). In this study, we use daily average temperature and salinity at different depth from the surface to 500-m depth between January 2006 and December 2013 to compare with Argo float estimates (NOAA/PMEL 2014). Comparisons are made for a few moorings sites chosen for their location and length of the time series.

c. Remote sensing datasets

Data from satellite altimeters are used in this study through the Archiving, Validation, and Interpretation of

FIG. 2. Number of Argo profiles in the equatorial Pacific in 10-day windows from January 2004 to August 2014 in the 10°S–10°N band of latitude (red) and 2°S–2°N (blue).

Satellite Oceanographic Data (AVISO) delayed-mode merged product from January 2004 to October 2014. This consists of gridded sea surface height (SSH) combining all available satellite altimeters (Ducet et al. 2000). The 2014 SSALTO/Data Unification and Altimeter Combination System (Duacs) product (DUACS 2014) consisting of daily maps with a $1/4^\circ \times 1/4^\circ$ spatial resolution is used (CNES 2014). For this study, anomalies from the 2006–13 time mean are considered after being linearly detrended for the period 1993–2013. In addition, sea surface temperature (SST) from the NOAA Optimal Interpolation SST product (NOAA OISST; Reynolds et al. 2002) for the period 2004–14 is also used.

3. Optimal interpolation

We first describe characteristics (covariance and noise) used in the OI of Argo profile data to obtain temperature and salinity fields between January 2004 and August 2014. The OI procedures are similar to RG09, but they focus on the equatorial Pacific rather than consider the global ocean. Following RG09, a 10-yr mean and climatological monthly fields (“first guess”) are estimated by a weighted least squares procedure (Ridgway et al. 2002). Then, an objective analysis is made of the anomaly time series formed by subtracting this first guess from the data (Bretherton et al. 1976). The OI can feed back onto the estimate of the annual cycle.

Each anomaly $\phi^{\text{obs}}(x, t)$ with $x = 1, \dots, N$, where N is the number of observations at time t , can be expressed as a sum of the signal ϕ (true value) and the noise ϵ (assumed independent and stationary). The OI consists of an estimate of the variable $\theta(x, t)$ from a weighted linear combination of observations ϕ_i^{obs} located at irregular points in space and time (Bretherton et al. 1976; Wilkin et al. 2002).

The estimation $\hat{\theta}(x, t)$ on a regular grid is

$$\hat{\theta}(x, t) = \mathbf{CA}^{-1}\phi^{\text{obs}}, \quad (1)$$

where $\mathbf{C}$ is the *estimate-data* covariance matrix $C_{ij} = \langle \hat{\theta}_i \phi_j^{\text{obs}} \rangle$ and $\mathbf{A}$ is the *data-data* covariance matrix, which is defined as

$$A_{ij} = \langle \phi_i^{\text{obs}} \phi_j^{\text{obs}} \rangle = \langle \phi_i \phi_j \rangle + \langle \epsilon_i \epsilon_j \rangle = \langle \phi_i \phi_j \rangle + \epsilon^2 \delta_{ij}. \quad (2)$$

In this work, the accuracy of the data covariance function $\mathbf{C}$ and the noise-to-signal ratio are improved with respect to RG09 in order to optimize the estimation and for a more realistic error. The estimated error from the OI depends on the measurement array (data spacing) and on the details of the covariance function (including noise and the chosen spatial/temporal scales) (Walker and Wilkin 1998; Davis 2005). Therefore, we focus initially on the covariance function and then investigate the impacts of different sampling strategies.

a. Data covariance

As a start in estimating a covariance function for use in the mapping, the sample covariance is computed from the observations. The sample covariance uses pairs of steric height (SH) anomalies from the climatological monthly fields, separated in time by less than 1 day and in latitude/longitude by increments of 0.5° in both the zonal and meridional directions (Fig. 3). Both temperature at different levels (not shown) and 0–2000-dbar SH sample covariances (Fig. 3) are similar and show a pronounced zonal elongation at the equator mainly due to the impacts of planetary waves and interannual variability. The sum of a small-scale Gaussian and a large-scale exponential function is used to approximate the sample spatial covariance as in RG09, and added a temporal Gaussian function (15-day scale) as Ducet et al. (2000) or Guinehut et al. (2012).

FIG. 3. Normalized (top) zonal and (bottom) meridional covariance of SH (0–2000 dbar) anomalies, as a function of latitude, (left) estimated from the 10 years of Argo data (2004–13), (middle) as approximated in functional form for objective analysis of temperature and salinity fields in [RG09](#), and (right) as in (middle), but with the modified G15 spatial decorrelation scales (see text).

$$c(d, t) = \left[0.77 \exp\left(\frac{-d^2}{200}\right) + 0.23 \exp\left(\frac{-|d|}{1666}\right) \right] \times \exp\left(-\frac{t^2}{15^2}\right), \quad (3)$$

where t is the temporal distance (days) and d is the spatial distance (km) defined as

$$d = \sqrt{\left(\frac{\text{dist}_x}{\text{xscale}}\right)^2 + \left(\frac{\text{dist}_y}{\text{yscale}}\right)^2} \quad (4)$$

with dist_x , dist_y being the horizontal distance between points in the zonal and meridional directions, respectively. To represent the zonal elongation of correlation in the tropics, $(\text{dist}_x, \text{dist}_y)$ are scaled by a factor $(\text{xscale}, \text{yscale}) = (1, 1)$ for latitudes equal to 15° , increasing linearly to $(\text{xscale}, \text{yscale}) = (3.5, 2)$ at the equator.

Unlike the monthly data binning of [RG09](#), here the OI includes the time domain and is estimated every 5 days with a 60-day temporal window (data are included up to

30 days before and after the given date). This explicit temporal covariance (15-day decay scale), combined with the higher time resolution of grid points, will improve the estimation of intraseasonal variability. In addition, in order to avoid potential misinterpretation of equatorial wave phenomena, no propagation term is included in the OI as in some altimetric or combined Argo–altimetric estimates, such as [Ducet et al. \(2000\)](#) and [Guinehut et al. \(2012\)](#). In the OI, the normalized covariance weights data depending on their space and time distances to the estimated point. For the rest of the paper, this more accurate covariance function is used, where [Gasparin et al. 2015](#), hereafter G15 is used for comparison with the [RG09](#) covariance function ([section 4c](#)).

The choice of using a covariance function based on SH calculated for the entire tropical Pacific is a crucial point for temperature/salinity estimation and errors. Temperature is the leading contributor to SH in the tropics. However, salinity can have a strong impact, especially in the western tropical Pacific ([Maes et al. 2002](#); [Ueki et al. 2002](#)). Unlike temperature, salinity has shorter spatial decorrelation scales, and the western Pacific seems to have reduced equatorial elongation, as a result of the

TABLE 1. Statistics of Argo comparison with TAO/TRITON temperature at the thermocline level and altimetric SSH estimations at three locations along the equator. Total-resolved signal (tot-res) is obtained after a low-pass filtering with a 20-day running mean and further with a 100-day running mean to separate the total-resolved signal into intraseasonal (intra) and low-frequency (low-freq) time scales. The standard deviations (std dev) of the total-resolved signal of Argo temperature and Argo SH and their RMS difference (RMS diff) with TAO/TRITON temperature and altimetric SSH are indicated to highlight the spatially variation of the signal. “%DV” indicates the percentage of the daily variance of TAO/TRITON temperature (and weekly variance for SSH) represented by the total-resolved signal. “%RV” is the percentage of total-resolved variance of TAO/TRITON and SSH represented by Argo estimates.

	%DV	RMS diff			Std dev	%RV
		Tot-res	Low freq	Intra		
Argo temp vs TAO/TRITON						
0°N, 165°E, 150 m	80	0.6	0.4	0.4	2.1	92
0°N, 140°W, 100 m	88	0.8	0.6	0.5	2.6	91
0°N, 110°W, 50 m	80	0.8	0.7	0.5	2.8	94
Argo SH vs SSH						
0°N, 165°E	80	1.6	1.3	1.0	3.9	82
0°N, 140°W	90	1.7	1.1	1.4	6.7	94
0°N, 110°W	88	1.7	1.1	1.3	5.8	91

salinity effects (see supplemental Fig. 2). After many experiments, we decided to use the same covariance function for both temperature and salinity from the SH calculated for all of the tropical Pacific without distinguishing between the western and eastern regions. Separating the western and eastern Pacific reduces the number of available data, resulting in a noisier covariance function and also requiring a smooth transition between regions. A number of experiments were performed with different covariance functions, but for reasonable choices the estimations did not change substantially. Questions remain open regarding regional representation of salinity covariance in the western and eastern tropical Pacific, and these will require further examination and consideration when more data are available.

b. Noise-to-signal variance ratio

The total variance of the observed field is the sum of the signal and noise variances. The noise corresponds to the unresolved variability in time and space of the signal (geophysical noise), plus random instrumental errors (Kessler et al. 1996). For uncorrelated noise, the noise-to-signal variance ratio is added to the main diagonal of the *data–data* covariance matrix **A** [Eq. (2)]. Here, the total variance in SH is estimated to be 67 cm² based on all the 0–2000-m SH anomaly pairs between 10°S and 10°N. On the other hand, the noise variance is estimated to be 11 cm² by using SH anomaly pairs having short separation in both time and space (<1 day, <50 km). Hence, the signal variance is 56 cm² and the noise-to-signal variance ratio is about 0.20. As we will see in the following, the signal variance is inhomogeneous along the equator. The question of whether it is preferable to approximate the noise-to-signal ratio as constant, or noise as constant while the signal variance is variable,

is a reasonable one because the noise is less spatially variable than the signal. But, several experiments were performed in which the noise-to-signal ratio was varied by a factor of 2, and impacts on the estimated fields and associated errors were low. For this reason and for simplicity, the constant noise-to-signal ratio is used for the equatorial Pacific.

4. Assessment of ocean observing systems

To evaluate the quality and consistency of the interpolated Argo temperature/salinity estimates as well as the associated errors, they are compared with two independent datasets—temperature/salinity from TAO/TRITON moorings and SSH from satellite altimeters. The first objective is to assess how well Argo is observing both intraseasonal and seasonal-to-longer-term variability in the equatorial Pacific. Time scales shorter than 20 days are not considered because they are unresolved by the 10-day sampling intervals of most Argo floats and of the TOPEX/Jason altimeter. This unresolved variability may be important, being associated with processes such as tropical instability waves (10–40-day variability; Lee et al. 2012) and the diurnal cycle (Kessler et al. 1996). The fraction of variance retained after filtering each daily TAO/TRITON time series (and weekly altimetric SSH) with the 20-day running mean is between 80% and 90% of the unfiltered variance at equatorial sites and is recorded in Table 1. An issue for future investigation is how much of the unresolved variability could be captured through shorter Argo cycle times or additional Argo floats. The three gridded datasets—Argo, TAO/TRITON, and SSH—are each filtered with a 20-day running mean to represent the “total-resolved variability” that is resolved by all three observing systems. Next, each gridded dataset is filtered

with a 100-day running mean to represent “seasonal-to-longer-term variability.” Finally, the difference between the 100- and 20-day smoothed series is referred to as “intraseasonal variability,” though it is noted that variability shorter than 20 days is excluded. Here, and in the following, we use the term “percent of represented variance” as the comparison metric, calculated as 1 minus the proportion of the residual variance (e.g., the variance of the difference between independent data divided by the signal variance). The TAO/TRITON dataset has temporal gaps, and for the present calculation, only points having 10 days of data before and after the given day are retained (50 days for the low-frequency/intraseasonal separation). Sensitivity tests were performed by changing the shape of the smoothing filter (Hanning/raised cosine, Triangle/triangle, Welch/parabolic) but keeping the same frequency limits, and these produced similar results.

a. Comparison of Argo estimates with independent datasets

Here the aim is to estimate Argo’s capabilities for representing subsurface temperature variability in the thermocline and salinity in the surface layer. These are key indices of the ocean state and of ocean–atmosphere exchanges. The TAO/TRITON data have been smoothed in time, as noted above, but are representative of a point in space, while the Argo and altimetry interpolations are for space/time grid cells, and hence smoothed both spatially and temporally. It is likely that the temporally smoothed TAO/TRITON time series is representative of a larger region than the unsmoothed time series. But in any case, the difference between the Argo and altimetry representations and that of temporally smoothed TAO/TRITON data constitutes an upper bound for the difference between equivalently smoothed fields.

1) TEMPERATURE

To ensure that the comparison of Argo and TAO/TRITON estimates is spatially representative, three sites are chosen spaced widely along the equator and having long time series (165°E, 140°W, 110°W). Temperatures are compared for the period 2006–14, when Argo had achieved its objective of $3^\circ \times 3^\circ$ spacing in the equatorial Pacific (about 300 profiles every 10 days; 10°S–10°N; Fig. 2). Comparisons of 100-m temperature are shown for the mooring site 0°N, 140°W in Figs. 4a–c. The 100-m level corresponds to the thermocline depth at this location and is associated with the maximum in signal variance.

At 0°N, 140°W, the Argo temperature at 100 m shows good consistency with the 20-day smoothed TAO/TRITON time series, having an RMS difference of 0.81°C. The

interpolated Argo data capture 91% of the variance of the 20-day smoothed TAO/TRITON time series (Fig. 4a). For the low-frequency temperature time series, Argo and TAO/TRITON estimates have an RMS difference of 0.56°C (~95% of the variance is represented), reproducing clearly the transition from the El Niño events of 2006–07 and 2009–10 to the La Niña events of 2007–08 and 2010–11 (Fig. 4b). This confirms that the design of the Argo array is appropriate to represent seasonal-to-longer-term variability along the equator (RG09). At intraseasonal time scales, Argo represents around 77% of the TAO/TRITON 0°N, 140°W temperature variance at 100 m (RMS difference estimated at 0.50°C). Even at these shorter time scales, there is a good representation of the occurrence and varying amplitude of intraseasonal oscillations. The same calculations made at two other sites along the thermocline as well (0°N, 165°E and 0°N, 110°W) indicate similar percentages of TAO/TRITON-represented variance and RMS differences (Table 1). Moreover, RMS difference reaches its maximum along the thermocline, presenting statistics of Table 1 as an upper bound for the difference between Argo–TAO/TRITON estimations (see supplemental Fig. 3).

In addition to the 60-day binning of Argo data (a 30-day window before the date and a 30-day window after), estimates were made using only the one-sided 30-day window preceding the date of the estimate. These showed that the TAO/TRITON variance represented at these three sites decreased by only 3%–5% for the different time scales (quasi-identical RMS differences), using the one-sided windowing. The decrease in represented variance is small because of the long spatial and temporal correlation scales in the equatorial waveguide. This demonstrates the Argo array’s ability to contribute to near-real-time monitoring of variability on time scales longer than 20 days—an important attribute of an operational observing system.

2) SALINITY

Salinity is an important element in ENSO and tropical Pacific variability through mixed layer/barrier-layer evolution, frontal dynamics, and its contribution to horizontal pressure gradients. As well as being dynamically significant, salinity is a key diagnostic of the atmosphere–ocean freshwater balance. Measurements of salinity in the TAO/TRITON array are much sparser than for temperature. The three westernmost moorings (137°, 147°, 156°E) provide most of the salinity sampling along the equatorial Pacific. We present in Figs. 5a–c a comparison between Argo and TAO/TRITON salinity at 50-m depth at 156°, 0°N, where the variance is relatively high. The datasets show good consistency in representing the strong variability at this location, and even with the large

FIG. 4. (a)–(c) TAO/TRITON mooring temperature (black) and Argo temperature (red) at 0°N, 140°W at 100-m depth and (d)–(f) sea level anomaly derived from SSH (black) and Argo SH (γ is the linear regression coefficient of SH onto SSH) for the (top) total-resolved, (middle) seasonal-to-longer-term, and (bottom) intraseasonal time scales during 2006–14.

RMS difference of ~ 0.17 , Argo represents 85% of the TAO/TRITON salinity variability. For seasonal-to-longer-term variability, Argo data capture the strong freshening of the 2006/07 and 2009/10 El Niño events. In terms of intraseasonal variability, again the time series show qualitative consistency, with an RMS difference of 0.10. In the right panels of Fig. 5, the RMS difference between the surface and 500 m shows that the largest values are at the sea surface, while for temperature the largest differences were at thermocline depth. Thus, although the near-surface salinity signals are large, interpolation errors in salinity in the western Pacific are still important and can reach more than 0.2 in the surface layer. In the central-eastern Pacific, moored salinity observations are sparse but the salinity effects are expected to be lower.

Salinity effects on SH variations have been previously studied (Maes et al. 2002; Ueki et al. 2002). As a vertical integral of the specific volume anomaly, SH is a function of temperature, salinity, and pressure. Salinity contributions can be estimated by subtracting SH, with salinity replaced by the mean value from SH with the observed salinity included (Maes et al. 2002). These

computations result in a salinity contribution to SH that is strongly related to ENSO and can reach +5 cm during moderate El Niño and –5 cm during La Niña (not shown).

The effects of salinity and temperature errors on density estimations are estimated in a similar way. First, Argo density is calculated using observed Argo salinity and temperature values. Next, the calculation is repeated using temperature plus temperature error, with the latter defined as the difference between Argo and TAO/TRITON temperature. This corresponds to assess effects of temperature errors on density estimation. A similar calculation is made for salinity and salinity error, and a conclusion is that below 100 m density error is mainly driven by temperature error, while in the surface layer salinity error dominates error in density estimation (Fig. 6). This highlights the importance of salinity measurements, especially in the surface layer in the western Pacific. The calculation was repeated in the central and eastern Pacific, and although with many fewer moored salinity measurements, it appeared that salinity contributions are less important (Ueki et al. 2002).

FIG. 5. (a)–(c) TAO/TRITON mooring salinity (black) and Argo salinity (red) at 0°N, 147°E at 100-m depth for the (top) total-resolved (periods longer than 20 days), (middle) seasonal-to-longer-term (periods longer than 100 days) and (bottom) intraseasonal (periods between 20 and 100 days) time scales during 2006–14, and (d)–(f) RMS difference as a function of depth for the three equatorial TRITON moorings at 137°E (black), 147°E (red), and 156°E (blue).

3) ARGO SH AND ALTIMETRIC SSH

The quality of Argo estimates is also assessed by comparing the Argo SH (0/2000 dbar) with altimetric SSH, considering the latter to approximate vertically integrated subsurface density or temperature (Figs. 4d–f). However, unlike Argo SH, altimetric SSH includes not only the 0–2000 dbar upper-ocean steric component, but also deep steric (below 2000 dbar) and mass-related components. To account for a portion of these differences, a simple linear regression coefficient γ ($\text{SSH} \simeq \gamma \text{SH}$) is determined using Argo SH and the collocated altimetric

SSH (Guinehut et al. 2004; Dhomps et al. 2011; Guinehut et al. 2012) with

$$\gamma(x, y) = \frac{\langle \text{SH}(x, y) \text{SSH}(x, y) \rangle}{\langle \text{SSH}(x, y) \text{SSH}(x, y) \rangle}, \quad (5)$$

where SH and SSH denote anomalies from the 2006–13 mean, and the angle brackets ($\langle \rangle$) indicate covariances.

In the equatorial region, the vertical structure of the ocean is mainly upper-ocean baroclinic, with regression coefficients around 1.0–1.1 (Guinehut et al. 2004; Vinogradova et al. 2007; Dhomps et al. 2011; Guinehut

FIG. 6. Density differences between Argo and Argo plus Argo-TAO/TRITON differences for salinity (red) and temperature (black).

et al. 2012; Zajaczkowski and Gille 2015, manuscript submitted to *J. Geophys. Res. Oceans*) At 0°N , 140°W , the Argo SH (multiplied by 1.04 per the linear regression) and the altimetric SSH have a good fit. Argo SH is able to represent more than 90% of the altimetric SSH variance for the total-resolved (RMS difference of 1.7 cm) and seasonal-to-longer-term (RMS difference of 1.1 cm) signals. The percentage decreases to 71% for the intraseasonal variability (RMS difference of 1.4 cm). The fit is similar for other longitudes (Table 1). Thus, Argo captures the dominant SH component of SSH with good accuracy on time scales of 20 days and longer.

b. Combining sea surface height and Argo temperature

As major components of the ocean observing system, remote sensing satellites have provided synoptic observations of SSH and SST spanning the global ocean for

more than two decades. Above we considered temperature, salinity, and SH estimates using Argo data alone, keeping TAO/TRITON and altimetric SSH as independent datasets for the evaluation of these estimates. Here we ask to what extent the estimation of subsurface temperature can be improved using a combination of altimetric SSH and Argo temperature.

First, a synthetic temperature at 100 m (T_{syn}) is estimated from SSH and SST through a multiple linear regression following Guinehut et al. (2012). A $1^{\circ} \times 1^{\circ}$ spatial grid is considered for the three datasets, with the same 20-day smoothing as used above. Similar to Fig. 4, T_{syn} is compared to TAO/TRITON observations (Figs. 7a–c). At 0°N , 140°W , T_{syn} represents 88% of the total-resolved TAO/TRITON 100-m temperature variance (RMS difference of 0.92°C), around 70% of intraseasonal variance (RMS difference of 0.59°C) and 92% of seasonal-to-longer-term variance (RMS difference of 0.64°C). This representation demonstrates good consistency between in situ and proxy remote sensing observations at 0°N , 140°W , but it is noted that altimetry-TAO/TRITON RMS differences are higher than Argo-TAO/TRITON RMS differences by 0.1°C (Figs. 4, 7).

Next, T_{syn} is combined with Argo data in the OI by using T_{syn} as the first guess rather than the climatological monthly mean (see section 3). The subsequent objective analysis is performed using anomalies formed by subtracting the first-estimate T_{syn} , linearly interpolated to Argo profile locations in space and time. The mapping covariance has been adapted to these anomalies with a noise-to-signal ratio of 0.4 and by reducing the length scales to $(\text{xscale}, \text{yscale}) = (2, 1)$ at the equator (see section 3). As expected, this estimate gives a better fit to TAO/TRITON estimations and can represent more temperature variance than T_{syn} alone (Figs. 7d–f). Disappointingly, the combined estimate is not a large improvement compared to Argo alone or SSH alone, especially at intraseasonal time scales (Figs. 4d–f). Given the smaller decorrelation scales, the 2006–13 Argo network is probably too sparse for substantial improvement of the T_{syn} estimate. However, we can expect that the enhanced Argo resolution along the equator that began in early 2014 may be better suited for this combination with altimetry. Similar experiments might be carried out using data assimilation models, to test whether our statistical approach is robust.

c. Error estimates from different sampling strategies

Accurate error estimates are essential for assessing and designing sampling strategies. The quality of error estimates from OI is difficult to assess because it requires comparison with independent datasets; that is, a characteristic of OI is that, depending on the density of

FIG. 7. Temperature at 0°N, 140°W at 100-m depth from TAO/TRITON mooring (black) and (a)–(c) regressed from altimetric SSH (blue), (d)–(f) from an OI using Argo anomaly from T_{syn} for the (top) total-resolved (>20 days), (middle) seasonal-to-longer-term (>100 days) and (bottom) intraseasonal (between 20 and 100 days) signals during 2006–13.

observations, small differences in the covariance function lead to relatively small differences in the estimated field but to relatively larger differences in estimated errors (Davis 2005). The evaluation of the OI-estimated error is made here by comparing it with differences between estimated fields from Argo and TAO/TRITON temperature, an independent dataset. Similar experiments have been made for assessing salinity errors, but the results are less conclusive (not shown). Salinity errors from the OI are not sufficiently consistent with the TAO/TRITON comparative difference, especially in the surface layers, either due to insufficiency of the salinity covariance function or to drift of the moored salinity sensors (Ando et al. 2005). Therefore, quantitative analysis of the OI error is confined to temperature.

As an example, Fig. 8 shows the comparison of 100-m TAO/TRITON and Argo temperatures at 0°N, 140°W, with associated error bars on the Argo estimate (in green), based on the RG09 covariance and on our “new” covariance function, G15. First, the mean difference of the Argo-estimated fields in relation to TAO/TRITON, which is a measure of bias in the datasets, is

less than 0.1°C for both covariance functions. Second, both Argo-estimated fields have similar RMS differences with the TAO/TRITON mooring at 0°N, 140°W: 0.9°C for RG09 and 0.8°C for G15, and similar differences are observed at other longitudes (not shown), confirming the small impacts of the covariance function on the estimated fields. With the 20-day independent bins totaling 128 for the period 2006–13, the standard error of the mean difference (RMS difference divided by the square root of the number of independent data) is estimated at 0.08°C, so the RMS differences are consistent within the error. The standard deviation of the TAO/TRITON temperature is 2.6°C, equal to that using G15, while the RG09 temperature standard deviation is only 2.2°C (Fig. 8). In this figure, it can be seen qualitatively that errors from the G15 covariance function are lower than RG09 and are more consistent with the differences between the OI estimates and the independent data. In fact, RG09 has an RMS error of 1.8°C, equivalent to an overestimation by around 100% of the corresponding OI–TAO/TRITON differences. By contrast, the RMS from the G15-estimated errors is 0.8°C,

FIG. 8. TAO/TRITON mooring temperature (black) and Argo temperature (red) at 0°N , 140°W at 100-m depth for the total-resolved signal (>20 days) between 2006 and 2013 using (top) the RG09 mapping and (bottom) G15 mapping. Green indicates the associated OI error bar.

consistent with the TAO/TRITON comparison. In general, the G15-estimated error is lower than RG09 and is more consistent with OI minus independent observations (see supplemental Fig. 3), and this is an important feature for assessing sampling strategies in the following.

To assess different sampling strategies, errors are estimated for horizontal maps of the temperature anomaly at the time-mean depth of the $\sigma = 25$ surface (pycnocline) from 10°S to 10°N and on an equatorial vertical section between the sea surface and 280 m. The variance of these temperature anomalies (Fig. 9) reflects mainly

the vertical displacement of the thermocline due to the local and remote wind forcing acting on the stratification. Spatially, the largest temperature anomaly variance is found in the eastern-central Pacific between 160° and 100°W , where large values between 4° and 10°N reflect strong variability in the North Equatorial Countercurrent. Between 4°S and 4°N , equatorial waves are responsible for most of the vertical displacement of the thermocline, and values along the equator are lowered somewhat by the reduced stratification in the core of the Equatorial Undercurrent relative to off-equatorial locations. On the equatorial vertical section, large variability

FIG. 9. Temperature variance ($^{\circ}\text{C}^2$) (top) at $\sigma = 25$ mean depth and (bottom) along the equator (2°S – 2°N) between 0 and 280-m depth for the period 2006–13. Black lines indicate the mean depth of the 20°C isotherm (dashed) and $\sigma = 25$ isopycnal (full).

follows the core of the pycnocline/thermocline, shoaling to the east, with the highest variance found in the central-eastern Pacific. The highest variance of the thermocline does not coincide exactly with the $\sigma = 25$ mean depth, especially in the western Pacific, where the maxima in vertical stratification and in temperature variance are found at $\sigma = 24.5$. These patterns reflect the 2006–13 variability, including ENSO and some decadal variability, and they provide the context for comparison of observational strategies in the following.

Figure 10 shows estimated mapping errors in the tropical Pacific at the mean depth of the $\sigma = 25$ surface. The panels show the normalized error variance (OI

mapping error variance/signal variance), for four different sampling patterns. “TAO/TRITON array” gives errors for the actual sampling of the moored array for the period 2006–13; “2006–13 Argo average” and “May 2014 Argo” represent averaged variance error maps for actual float distributions in the period 2006–13 and for May 2014 (after the recent deployment of 41 floats along the equator), respectively. The last panel, “integrated system,” represents errors estimated for a combination including the TAO/TRITON array and the 2006–13 Argo coverage. As expected, normalized errors for the TAO/TRITON array are low at the mooring sites and increase zonally between moorings to more than 70% of

FIG. 10. RMS estimated errors as a percentage of temperature variance depending on sampling strategies. (a) TAO/TRITON array, (b) 2006–13 Argo coverage, (c) Argo in May 2014, and (d) integrated system, (combining TAO/TRITON array and the 2006–2013 Argo coverage) at $\sigma = 25$ mean depth.

the variance, and also increase poleward due to the shorter spatial scales there (Fig. 3). These are equivalent to an absolute error of 0.2°C near the mooring locations and of 2.0°C in the eastern-central Pacific between moorings. In comparison, Argo floats are randomly distributed, providing more homogeneous errors over the basin, except near the boundaries. The 2006–13 Argo coverage provides a zonal mean of the RMS error representing 25% of the variance along the equator (2°S – 2°N), equivalent to an error of 0.8°C . The May 2014 Argo error estimate is less homogeneous due to the shorter averaging period. Impacts of the recent deployment of Argo along the equator decrease the zonal mean of the RMS error estimate to 9% of the signal variance (0.5°C) (see supplemental Fig. 4). The integrated system, showing impacts of the TAO/TRITON array combined with the mean 2006–13 Argo coverage, has an RMS error of 19% of the variance (0.7°C) averaged over the time domain.

We repeat this comparison, focusing along the equator in the upper 280 m (Fig. 11). Because Argo and the TAO/TRITON array have relatively good vertical resolution in the upper water column, a vertical decorrelation scale has not been included, and so the relative

error is independent of depth. Relative error is reported in the top of each panel of Fig. 11, and in the bottom of each panel is shown the absolute time-mean error. Conclusions are qualitatively similar to those in Fig. 10 with respect to the TAO/TRITON, Argo 2006–13, Argo May 2014, and integrated system error distributions. Errors can be higher than 1.6°C for the TAO/TRITON array between moorings. Argo sampling has vertical maxima in absolute errors of 0.8°C for the 2006–13 distribution and 0.4°C – 0.6°C for the May 2014 enhanced Argo coverage. As expected, the integrated system decreases the absolute error to 0.2°C near the mooring sites.

Figures 10 and 11 demonstrate quantitatively different error characteristics of TAO/TRITON and Argo sampling with regard to estimation of upper-ocean properties. TAO/TRITON does a good job of estimating temperature at the mooring sites, with high temporal resolution, but errors are large between mooring sites. Argo has many more platforms in the TPOS domain but profiling occurs at much lower temporal resolution than the moorings. Thus, Argo's higher spatial resolution makes it better suited for studying spatial patterns of variability and propagation on intraseasonal and longer

FIG. 11. (top of each panel) As in Fig. 10 (normalized error variance for temperature), but along the equator (2°S – 2°N) and (bottom of each panel) absolute estimated errors between 0- and 280-m depth ($^{\circ}\text{C}$).

periods, but it is less well suited for studying variability on periods shorter than 20 days at point locations.

5. Representation of intraseasonal variability

As shown previously, Argo sampling captures most of the intraseasonal variability in temperature and SH in the equatorial Pacific upper ocean. Here the issue is explored further using as a case study the 2009/10 El Niño and the 2010/11 La Niña episodes, and describing the propagation of intraseasonal temperature anomalies along the equator. As mentioned previously, the intraseasonal variability of the tropical winds can affect the upper ocean through generation of equatorial Kelvin waves, and may represent a mechanism for the onset or evolution of El Niño (Wyrtki 1985; Kessler and Kleeman 2000). However, it has long been recognized that the transfer of momentum that drives the intraseasonal Kelvin waves' activity occurs over time scales of several days (Luther et al. 1983; Kessler et al. 1995; Harrison and Vecchi 1997; Vecchi and Harrison 2000), which are too short to be resolved by current Argo capabilities. By focusing on intraseasonal time scales in relation to ENSO, we investigate the degree to which a decade of Argo data provides the upper-ocean

variability spanning intraseasonal to interannual time scales.

a. Argo steric height and altimetric sea surface height

In Fig. 12, Argo SH, multiplied by 1.1 per the linear regression, and altimetric SSH are both filtered to extract the intraseasonal component as described in section 4. We focus on the 2009/10 El Niño and 2010/11 La Niña events because they present distinctively different features at intraseasonal time scales. During 2009/10 both fields reveal eastward propagation nearly spanning the basin, with a 60–70-day period, and with consistent structures in the form of propagating negative and positive anomalies of ± 6 – 8 cm at a speed of around 2.4 m s^{-1} , consistent with the first mode baroclinic Kelvin wave (Cravatte et al. 2003). From the date line to the eastern boundary, regressed Argo SH amplitude appears to be lower than that of altimetric SSH but, on average, it captures 82% of the intraseasonal variance of altimetric SSH between 180°E and 100°W during this event. For this period, the RMS difference of these two quantities is 2.4 cm, which could be explained by dynamical and sampling differences. In contrast, the intraseasonal component appears to be much weaker in both SH and SSH during the 2010/11 La Niña event with a maximum

FIG. 12. (top) Intraseasonal (20–100 days periods) Argo SH (cm) and (bottom) altimetric SSH (cm) during (left) July 2009–June 2010 El Niño event and (right) July 2010–June 2011 La Niña event along the equator (2°S–2°N).

anomaly amplitude of 2–3 cm. Eastward propagation seems to be present but with a longer period (100–120 days). Finally, perhaps because of the weak signal and the noise amplitude associated with the RMS difference of 1.3 cm for SH compared to SSH, there are no clear longitudinal or temporal features in these pulses.

Intraseasonal variability has been studied using SSH data because of its relatively high spatial and temporal resolution (Cravatte et al. 2003), or using the TAO/TRITON array (Kessler et al. 1995) with high temporal but low spatial resolution. By comparing SH and SSH, the capability of Argo to represent intraseasonal variability in the equatorial waveguide is seen.

b. Vertical thermal structure

Having considered some common and complementary aspects of Argo SH and altimetric SSH, here we focus on Argo's unique contribution to observing the vertical structure of upper-ocean anomalies. Thermocline and SST anomalies are related in the tropics, and so consistent depiction of the vertical thermal structure of the ocean, especially through the depth range of the thermocline, is essential to determine a balanced heat

budget (Boccaletti et al. 2004). Moreover, it has been shown that propagating equatorially trapped waves are a significant source of energy in the ocean and especially below the thermocline (Kessler and McCreary 1993). In addition, even if models have good skill in ENSO-related mechanisms, significant discrepancies remain between these models and observations, raising the issue of the actual role of linear long equatorial waves (Dewitte et al. 1999). Thus, observing the vertical structure in the equatorial oceans is important for improving the description and understanding of the equatorial waveguide in relation to ENSO mechanisms.

During early 2014, the deployment of 41 Argo floats along the equator in the Pacific coincided with a strong event of eastward intraseasonal energy. In the tropical western Pacific (130°–160°E), westerly winds with strength of at least 7 m s^{-1} appeared around 15 February and persisted for at least 15 days. These winds, corresponding to the definition of a WWE (Harrison and Vecchi 1997), can produce downwelling Kelvin waves that propagate eastward and cause warming in upper-oceanic conditions in the eastern Pacific (McPhaden 1999). In Fig. 13 the thermal structure along the equator between the sea surface and 280-m depth, filtered to

extract the intraseasonal component (as described in section 4), is displayed every 10 days from 17 February to 7 June 2014. The $\sigma = 25$ depth is shown approximating the thermocline depth. The SSH is shown in the top of each panel in order to display simultaneously the vertically integrated representation of subsurface density or temperature observed by satellites, as seen in Fig. 12, and in situ subsurface temperature from Argo.

On 17 February (Fig. 13a), a positive thermocline temperature anomaly ($+1^{\circ}\text{C}$) is seen in the western-central Pacific, while a negative anomaly (-2°C) is found east of 140°W . The positive anomaly, located above the $\sigma = 25$ isopycnal, indicates a downward deflection of the thermocline (upward deflection for the negative anomaly). These vertical displacements of the thermocline (around 20 m) are associated with variations of SSH, with a deep thermocline implying an anomalously thick warm layer (high SSH; Rebert et al. 1985; Kessler 2006). This relation is clearly observed on 17 February, for instance, where positive SSH anomaly is associated with positive temperature anomaly west of 140°W , compared with negative SSH and negative temperature anomalies in the eastern Pacific.

These anomalies propagate eastward along the equatorial thermocline. The positive temperature anomaly ($+2^{\circ}\text{C}$) and its associated SSH (7–8 cm) appeared in the middle of January (not shown) and their expansion and intensification continue from the end of February to April (Figs. 13a–f). The anomaly reaches its maximum of $2.5^{\circ}\text{--}3^{\circ}\text{C}$ around 14–24 March. The negative anomaly in the east observed on February 17 disappears at the end of March, while another smaller one appears in the west and propagates in April and May, following the strong westerly winds. Another positive temperature anomaly is observed in the western Pacific on 18 April, propagating eastward, but the amplitude and spatial extension are weaker. There is a strong contrast between the large and strong positive anomalies (temperature and SSH) propagating from February to mid-April, which result from wind forcings at the end of February, and the small and weak positive anomalies starting from mid-March.

Another aspect of this particular episode is the persistence of warm SST anomalies in the eastern Pacific from April to June and beyond (Figs. 13d–h). The negative thermocline temperature anomaly observed in the western Pacific at the end of March seems to merge with the positive SST anomaly in the eastern Pacific and to disappear between 8 and 18 May. The weak positive anomaly propagating from mid-April to June, in turn, merges with the warmer conditions in the eastern Pacific at the end of May. It seems that the positive thermocline temperature anomaly generated following the strong wind event is so sufficiently strong that surface oceanic

conditions in the eastern Pacific remain warmer for more than 3 months. This cold tongue warming following WWEs has been previously described (Vecchi and Harrison 2000; Harrison and Chiodi 2009).

In addition to the 8000-km breadth of the intraseasonal Kelvin waves, small-scale structures are observed in the anomaly center, and further investigation is needed to determine whether these are significant. The different stages of the formation and development of intraseasonal temperature anomaly along the equator are represented here with unprecedented details, allowing new questions to be raised concerning the upper ocean at intraseasonal time scales. Argo's representation of the vertical structure of the upper ocean constitutes an important feature. This eastward propagation associated with the first baroclinic mode Kelvin wave (Kessler et al. 1995; Cravatte et al. 2003) has been described using Argo profiles by Matthews et al. (2007, 2010) during the 2003–06 period. The increase of sampling resolution since 2006 (Fig. 2) and the more accurate covariance function used here provide a greater fraction of the intraseasonal variability.

6. Summary and discussion

Using more than 10 years of Argo temperature and salinity profiles (2004–14), a new mapping of the upper ocean in the equatorial Pacific, with high temporal resolution, is presented. Following RG09 procedures, which were formulated for describing monthly large-scale anomalies globally, here anomaly fields at 5-day intervals are constructed utilizing improvements in the optimal interpolation that include more accurate representation of zonal and meridional scales and the noise-to-signal ratio, and by including the time domain.

The comparison of the Argo 5-day maps with independent observations from the TAO/TRITON array, and with satellite SSH, highlights Argo's ability to represent 70%–80% of the variance at intraseasonal time scales (periods of 20–100 days) and more than 90% of the variance for seasonal-to-longer-term variability. The RMS differences between TAO/TRITON and Argo temperature are estimated at around 0.5°C for intraseasonal variability and between 0.5° and 0.8°C for the total-resolved and seasonal-to-longer-term variability. The RMS differences between altimetric SSH and Argo SH range between 1.0 and 1.4 cm for intraseasonal and longer-term variability and around 1.7 cm for the total-resolved variability. The Argo-alone estimation provides a more accurate estimate of subsurface temperature anomalies than does the SSH-alone estimation, which has an RMS difference higher by 0.1°C compared to the Argo-alone estimation. The combination

FIG. 13. (top of each panel) Intraseasonal (20–100 days periods) altimetric SSH (cm) from delayed-time AVISO product along the equator (2°S – 2°N) and (bottom of each panel) intraseasonal temperature anomaly ($^{\circ}\text{C}$) every 10 days from 17 Feb 2014 to 24 Sep 2014. Black line indicates the depth of the $\sigma = 25$ isopycnal.

of altimetric SSH and Argo temperature improves the Argo-alone estimation by reducing the RMS difference by around 0.2°C for the total-resolved variability and the seasonal-to-longer-term variability. By contrast, the intraseasonal variability is modestly improved by reducing the RMS difference by around 0.05°C . We also investigate the effects of salinity and temperature errors

on density estimations and demonstrate the importance of salinity measurements, especially in the surface layer in the western Pacific.

The consistency of error estimates from the OI is validated by comparing with TAO/TRITON temperatures. The RMS error of the G15 mapping is consistent with RMS differences between gridded Argo temperature and

TAO/TRITON, whereas RG09 overestimated errors by about 100%. Next, these error estimates are used to evaluate different sampling strategies, such as the TAO/TRITON array, the mean Argo coverage, and impacts of the recent deployment of 41 Argo floats, for enhanced coverage along the Pacific equator. While the TAO/TRITON array provides high-quality time series data at the mooring sites, estimated errors are large between moorings. Argo coverage has a more homogeneous distribution, providing more uniformly accurate estimation across the equatorial Pacific. Argo-like coverage is thus better suited for studying spatial patterns and propagating variability for time scales longer than 20 days. While the coverage of Argo is homogeneous (about one float every 1.5° of longitude along the equator following deployment of the 41 floats), the high temporal resolution of the fixed moorings is essential to understand processes on time scales shorter than 20 days. Impacts of the recent deployment along the equator include reduction of the RMS error along the equatorial thermocline from around 0.8° to 0.5°C . Because different observing system elements have different attributes and advantages, an integrated observing strategy should incorporate these elements appropriately. Here, an integrated system, composed of TAO/TRITON moorings and the 2006–13 Argo coverage, is evaluated with respect to variability longer than 20 days and shows that the RMS of estimated errors along the equatorial Pacific decreases from 25% to 19% of the temperature variance (0.8° – 0.7°C) when the mooring observations are added to Argo.

The OI 5-day maps provide accurate estimation of intraseasonal and longer-term variability. At intraseasonal time scales, the comparison of Argo SH with altimetric SSH shows consistency in representing the eastward propagation of Kelvin wave–like variability during ENSO events. The RMS difference of SH and SSH at intraseasonal time scales is around 2.4 cm with the Argo coverage of 2009–10, and this difference will decrease due to the recent deployments. In addition, Argo data provide high vertical resolution to depict equatorial variability through the upper 2000 m of the water column. The eastward propagation of intraseasonal temperature anomalies is observed with unprecedented detail. While variability has been separated into intraseasonal and longer-term bands, the 2014 Kelvin wave sequence shown in Fig. 13 is not mostly contained in the intraseasonal band. The dominant period of the “wave” is around 190 days, and the amplitude of the temperature anomalies is decreased substantially by the intraseasonal filtering. Anomalies from the annual cycle can reach 7°C , in contrast to the 2.5°C intraseasonal anomalies in Fig. 13 for 29 March. Much of the Kelvin wave

energy during 2014 seems not to be confined to the intraseasonal band and longer periods need to be included to accurately depict these phenomena. In addition, to understand the generation mechanism, higher-frequency variability may also need to be considered.

Argo-alone estimation is insufficient for representing time scales shorter than 20 days, which requires the combination of multiple datasets for better understanding the generation of ocean variability occurring over shorter time scales. Here, we have illustrated Argo’s capability to represent intraseasonal and longer-term variability in the tropical Pacific and quantified improvements that result from enhanced Argo coverage along the equator. The comparison with independent datasets provided confidence in Argo representation of the kinematics of intraseasonal oceanic Kelvin waves and showed how the TPOS is still evolving.

Several follow-on questions are suggested by the present study.

- (i) Eastward-propagating large-scale temperature anomalies in the equatorial upper ocean appear to include small-scale embedded features, especially in the core of the anomaly. Further investigation of these is needed to determine their significance and, in particular, to determine their persistence and propagation. This could be done once a multiyear record is available having the present enhanced along-equator Argo resolution.
- (ii) It has been demonstrated previously that WWEs impact upper-oceanic conditions along the equator, which influence the duration and zonal extension of the WWEs through ocean–atmosphere interaction (Kessler et al. 1995; Harrison and Vecchi 1997; Gebbie et al. 2007). During 2014, a second pulse of Kelvin wave energy was observed in August, but unlike in the 2009 El Niño event, this second pulse was weaker than the one earlier in the year. The understanding of differences between intraseasonal variability during El Niño and La Niña events, of the extent to which intraseasonal oscillations occur at preferred times during the annual cycle, and the eastward propagation characteristics and impacts on SST, will all improve with a longer time series of high-spatial-resolution observations.
- (iii) With the present enhanced spatial and temporal resolution along the equator, the description of tropical instability waves will be improved in regard to occurrence and vertical structure. Moreover, other high-frequency processes, including the diurnal cycle, could be better resolved through burst sampling and similar experiments with profiling float mission parameters.

In conclusion, a decade of Argo data has provided improved statistics of ocean variability in the tropical Pacific, and an opportunity to assess and redesign an integrated ocean observing system for this key domain in the global climate system. Following the groundbreaking TAO/TRITON array, which long provided the only time series in the tropical Pacific, new systematic observations of subsurface variability in the tropical Pacific are being made by the Argo program. There are presently, and will always be, spatial gaps in the Argo array, just as there are gaps in the TAO/TRITON time series. These observing system elements, also including satellite SSH, are complementary; Argo floats travel thousands of kilometers zonally every year on the equator, while moorings are at fixed points. Our objective has been to quantitatively characterize the capabilities of the observing system elements, individually and in combination, to enable better utilization of existing datasets, including Argo, and to contribute to evolving the design of the Tropical Pacific Observing System (TPOS).

Acknowledgments. Argo data were collected and made freely available by the international Argo program and the national programs that contribute to it (<http://www.argo.ucsd.edu>; <http://argo.jcommops.org>). Participation by D. Roemmich and J. Gilson is supported by U.S. Argo through NOAA Grant NA10OAR4320156 (SIO CIMEC). The statements, findings, conclusions, and recommendations herein are those of the authors and do not necessarily reflect the views of the National Oceanic and Atmospheric Administration or the Department of Commerce. F. Gasparin was supported by a postdoctoral fellowship of the Scripps Institution of Oceanography. The TAO/TRITON array is maintained through a multinational partnership involving institutions in the United States (NOAA), Japan (JAMSTEC), Taiwan (NTU), and France (IRD) (<http://www.pmel.noaa.gov/tao/>). The altimeter products were produced by SSALTO/Duacs and distributed by AVISO with support from CNES (<http://www.aviso.altimetry.fr/duacs/>). We thank J. Sprintall for her valuable comments and L. Lehmann for assisting with some processing. We also thank M. McPhaden and B. Kessler and three anonymous reviewers for their very helpful comments on how to improve the manuscript. Graphics were produced using the visualization program FERRET, a product of NOAA's Pacific Marine Environmental Laboratory.

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