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Evaluation of the Tropical Pacific Observing System from the ocean data assimilation perspective

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The drastic reduction in the number of observation data from the Tropical Atmospheric Ocean (TAO)/Triangle Trans-Ocean Buoy Network (TRITON) array since 2012 has given rise to a need to assess the impact of those data in ocean data assimilation (DA) systems. This article provides a review of existing studies evaluating the impacts of data from the TAO/TRITON array and other components of the Tropical Pacific Observing System (TPOS) on current ocean DA systems used for a variety of operational and research applications. It can be considered as background information that can guide the evaluation exercise of TPOS. Temperature data from TAO/TRITON array are assimilated in most ocean DA systems which cover the tropical Pacific in order to constrain the ocean heat content, stratification, and circulation. It is shown that the impacts of observation data depend considerably on the system and application. The presence of model error often makes the results difficult to interpret. Nevertheless there is consensus that the data from TAO/TRITON generally have positive impacts complementary to Argo floats. In the equatorial Pacific, the impacts are generally around the same level or larger than those of Argo. We therefore conclude that, with the current configuration of TPOS, the loss of the TAO/TRITON data is having a significant detrimental impact on many applications based on ocean DA systems. This conclusion needs to be kept under review because the equatorial coverage by Argo is expected to improve in the future.

Key Words: TPOS2020; ocean data assimilation; TAO/TRITON array; observing system evaluation; observing system experiment

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1. Introduction

Ocean Data Assimilation (DA) systems are very valuable tools for monitoring and forecasting the ocean and climate state. The systems synthesize ocean observation data with numerical ocean

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models, transforming the observation data into information which can be used effectively by society. Consequently, the effectiveness of ocean DA systems inevitably depends on the observation type, the quantity, and the quality of data acquired by the ocean observing system.

Development of ocean DA systems for the tropical Pacific progressed rapidly after the Tropical Atmospheric Ocean (TAO) array (e.g. McPhaden *et al*, 1998) was completed in the early 1990s (e.g. Ji *et al*, 1995; Rosati *et al*, 1995). The TAO array was originally constituted by Autonomous Temperature Line Acquisition System (ATLAS) buoys alone. It was reorganized to the TAO/Triangle Trans-Ocean Buoy Network (TRITON) array by upgrading ATLAS buoys west of 160°E to TRITON buoys in 2000, which contain more advanced instruments (e.g. Ando *et al*, 2005). Ocean DA systems now underpin the research community by reconstructing the three-dimensional oceanic variations from observations by TAO/TRITON array and other platforms in the tropical Pacific.

However, the TAO/TRITON array is currently in crisis. Many ATLAS buoys stopped their normal operation after June 2012, and their data returns have decreased to about 40% since 2013 (Tollefson, 2014). The number of TRITON buoys has also started to reduce since 2013. This degradation is a serious concern for the oceanographic and climate research community because the array has been considered the backbone of the Tropical Pacific Observing System (TPOS).

A TPOS 2020 Workshop was held on 27–30 January 2014 at Scripps Institution of Oceanography (SIO) in order to assess the impacts of this problem and to work out countermeasures (http://www.ioc-goos.org/tpos2020; accessed 20 May 2015). A major item on the agenda for the workshop was to evaluate the impacts of the loss of TAO/TRITON data on the ocean DA systems.

This article is an outcome from that workshop. It summarizes the current status of ocean DA systems using observation data from TAO/TRITON and other TPOS components, their requirements for observations, and studies evaluating the impacts of those observation data on the systems. This article focuses mainly on observations of physical parameters for the ocean interior, i.e. temperature, salinity, and current velocity (including those made at the surface), and sea surface height (SSH), because ocean modelling and DA systems generally calculate the time evolution of those parameters. It should be noted that TAO/TRITON atmospheric observations at the surface also affect ocean DA systems because those observations are often employed for estimating the atmospheric forcing data for the system. We leave discussion of the surface meteorological data to Balmaseda *et al* (2014), which is part of the workshop report.

Applications of ocean DA systems can broadly be classified into the following four categories: (i) El Niño-Southern Oscillation (ENSO) monitoring and seasonal-to-interannual (S-I) forecasting; (ii) short-to-medium range (generally less than 1 month) ocean forecasting; (iii) retrospective estimations of the ocean state and variability mainly for climate studies; and (iv) decadal predictions. In this article, we discuss the current status and requirements of ocean DA systems, and the impacts of the observations on the systems for each application separately, although many systems are being used for more than one application and over more than one time-scale. The article also describes the requirements of observations for validation, which are common among the systems for all applications categorized above.

This article is organized as follows. First, we introduce the current status of ocean DA systems and discuss their requirements in section 2. The variety of the observing system evaluation studies for TPOS is given in section 3. A summary follows in section 4.

2. Current status and requirements

2.1. Seasonal-interannual forecasting

Ocean DA systems as well as coupled ocean-atmosphere general circulation models (CGCMs) are essential components of S-I forecasting systems in operational centres. Since most predictability for S-I forecasts comes from ENSO, the estimation of the tropical Pacific Ocean state is vital for S-I forecasting systems. Ocean DA systems are also employed in operational centres for the monitoring of equatorial wave activity, variability of the equatorial thermocline, and other oceanic phenomena associated with ENSO.

Operational monitoring of the ocean interior state in the equatorial Pacific with ocean DA systems using the TAO array started in the early 1990s (e.g. Ji *et al*, 1995). At that early stage, the DA systems assimilated temperature profiles alone. Assimilation of SSH data started in the mid 1990s after the launch of the TOPEX (Ocean Topographic Experiment)/Poseidon satellite. Subsequently the rapid increase of Argo floats after 2000 motivated updates to the DA systems in order to assimilate salinity globally from Argo. Consequently most current ocean DA systems for S-I forecasting (hereafter SIDA systems) have the capacity to assimilate salinity profiles imposing a multivariate (mainly temperature-salinity) balance relationship (e.g. Fujii *et al*, 2011).

Current SIDA systems in operational centres generally use ocean general circulation models (OGCMs) with resolution typically 1° but with some equatorial refinement in the horizontal and about 10 m resolution in the vertical in the upper ocean. The resolution is restrained because of the large computational burden for S-I forecasting. The UK Met Office (UKMO), however, now uses a 1/4°-resolution ocean model for the ocean DA system and the ocean component of the CGCM for S-I forecasting (MacLachlan *et al*, 2015; Waters *et al*, 2015). The majority of the systems currently apply three-dimensional variational (3D-Var) assimilation schemes (e.g. the National Oceanic and Atmospheric Administration (NOAA)/the National Centers for Environmental Prediction (NCEP), the Japan Meteorological Agency (JMA), the European Centre for Medium-Range Weather Forecasts (ECMWF), and the UKMO). However, other sophisticated assimilation schemes are also used in other institutes (e.g. Ensemble Optimal Interpolation (EnOI) at the Australian Bureau of Meteorology (ABoM); Yin *et al*, 20111, static Singular Evolutive Extended Kalman (SEEK) filter at Mercator, France; Brasseur *et al*, 2005). Although most systems are forced by sea surface fluxes estimated from atmospheric DA fields which are calculated separately, the ocean DA system in NCEP is coupled with an atmospheric DA system on line (i.e. it is a weakly coupled DA system) and sea surface temperature (SST) in the ocean DA fields also affects atmospheric DA results (Saha *et al*, 2010). Development toward coupled DA has also started in other centres. Retrospective long-term (typically 20–30 years) ocean DA runs or 'reanalyses' are often performed with SIDA systems in operational centres for validation and calibration of SI forecasting systems. These runs can be used for estimating forecast biases in order to correct forecasts for model error, and for skill assessment. Reanalyses are also used in climate research (section 2.3).

SST data are assimilated in SIDA systems as essential data because SST anomalies over the whole tropical Pacific are important features of El Niño/La Niña, and directly affect the atmospheric global circulation and climate. SST data are generally resampled to about 1° resolution before being assimilated with a typical sampling interval of 1 day. These spatial resolutions and temporal intervals generally seem to be sufficient for reconstructing the variability associated with ENSO. The horizontal distribution of SST is well observed from satellites and calibrated using *in situ* observations including the data from the mooring buoys. Gridded datasets of observed SST are provided from several operational centres.

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Assimilation of subsurface temperature observations is also essential for ENSO monitoring and S-I forecasting because variations of thermocline depths play important roles in the ENSO mechanism. In particular, there is a general consensus that baroclinic Kelvin wave activity along the Equator frequently affects occurrences of El Niño/La Niña. Considering the horizontal scale of these phenomena, required sampling intervals in the zonal and meridional directions are 500–1000 km, and around 200 km, respectively (e.g. McPhaden *et al*, 1998). The meridional interval is smaller due to the stretched structure of the equatorial waves in the zonal direction, but it is still not too demanding. The TAO/TRITON array was originally designed considering these requirements, and used solely for monitoring temperature variability associated with ENSO (e.g. McPhaden, 1999). Assimilating temperature profile data from the TAO/TRITON array is thus considered to be effective for detecting thermocline changes associated with ENSO. However, the vertical sampling interval (20–50 m around the thermocline) may not be sufficient to detect variability of the thermocline depth accurately. Considering the typical vertical resolutions of SIDA systems, a vertical interval around 10 m is desirable near the thermocline. In contrast, the sampling interval of TAO/TRITON array in the temporal direction (1 h) is very short compared to the time-scale of target phenomena. Time averaging is often performed before assimilating the data into the systems in order to reduce high-frequency noise and the number of observation data. Thus, the advantage of TAO/TRITON array (i.e. high frequency of data) is not fully utilised in current SIDA systems.

Temperature profiles observed by Argo floats are major components of *in situ* observations assimilated into SIDA systems, and complement the TAO/TRITON data. These floats have higher vertical and zonal resolutions (l m and 300 km), and their temporal sampling interval (10 days) is reasonable for ENSO. The meridional sampling interval, however, is somewhat larger than the TAO/TRITON array. The floats tend to be moved away from the Equator due to the need of long-period floats to remain at the surface for Argos data communication and the divergence of the equatorial near-surface current. However, since January 2014 Argo floats equipped with Iridium communication technology are being deployed along the Equator in the Pacific (Roemmich *et al*, 2014). Iridium communication will significantly reduce float times at surface (Rudnick *et al*, 2014), allowing floats to stay near the Equator longer than before, thereby making Argo a suitable observing system for detecting equatorial wave activities in a similar fashion to the TAO/TRITON array.

Variability of the thermocline depth can also be detected by SSH observations, and therefore the majority of SIDA systems assimilate SSH data from satellites. The sampling interval across the SSH satellite paths is 100–300 km (the interval along the paths is $\sim$7 km) and the temporal interval is 10–40 days. These intervals are reasonable for detecting ENSO-scale variability. However, the impact of assimilating SSH is generally small. First, the information from SSH observation is overlapped with that from subsurface temperature data obtained by TAO/TRITON and Argo floats. Second, the complicated vertical structure in the equatorial region makes it difficult to infer the vertical distribution of temperature anomaly from SSH which offers only vertically integrated information on the temperature and salinity fields. In addition, the assimilation of altimeter SSH requires a mean dynamic topography (MDT), which is derived from a combination of *in situ* and satellite observations and ocean circulation models (e.g. Maximenko *et al*, 2009), and is often poorly specified.

Considering the possibility that Tropical Instability Waves (TIWs) in the eastern tropical Pacific and complex structures in the far western equatorial Pacific (e.g. New Guinea current systems) affect ENSO (e.g. Ueki *et al*, 2003; Menkes *et al*, 2006), observed temperature or SSH data with higher spatial and temporal resolution may have some potential. Although the high-resolution data cannot be effectively utilized for the current suite of lower-resolution SIDA systems, it could be better exploited with the use of higher-resolution (1/4° or finer) ocean models expected to be adopted in the coming years.

The importance of near-surface salinity fields for ENSO prediction has been discussed in the last 20 years (e.g. Roemmich *et al*, 1994; Maes *et al*, 2005). It affects SST through the stability of stratification (e.g. the barrier layer), and the advection of warm water (e.g. fresh water jet). These features are particularly important around the equatorial salinity front due to the large variability of the salinity fields there. Most ATLAS buoys observe sea surface salinity (SSS), while TRITON buoys observe SSS and subsurface salinity. However, these data are not enough for SIDA systems to reproduce the salinity fields around the front, which has meridional scales on the order of 100–200 km. Vertical resolution of the tropical moorings is also insufficient for reproducing the influence of salinity fields on SST and near-surface temperature.

Argo floats are powerful tools for observing salinity profiles. Although their meridional resolution is still insufficient due to limited sampling near the Equator, the vertically high-sampling profiles have substantial impacts on the reproduction of the salinity fields (e.g. Balmaseda *et al*, 2007). SSH data also have an ability to detect the salinity variability when temperature profiles are well observed by other measurements and salinity has large variability (e.g. Fujii and Kamachi, 2003). Efforts to assimilate SSS observations from satellites such as Soil Moisture and Ocean Salinity (SMOS; e.g. Reul *et al*, 2014) and Aquarius (e.g. Lee *et al*, 2012) are emerging and the related impacts are being assessed (e.g. Toyoda *et al*, 2015). Although the accuracy of the satellite SSS observations (more than 0.2 PSU (practical salinity unit) for monthly mean with 150 km horizontal resolution) does not satisfy the requirements for DA (ideally less than 0.1 PSU in 10-day mean), it may benefit the detection of the SSS variability associated with ENSO, TIWs, and migration of the SSS fronts.

Data from ship observations are too sporadic spatially and temporally to adequately constrain the basin-wide variability of the thermocline depth and the salinity variability via assimilation. However, snapshots of vertical sections from shipboard measurements give useful insight into the structures of temperature and salinity fields. These sections promote our understanding and are also useful to validate the DA results. Ocean current data is assimilated in few ocean DA systems because of severe contamination by tidal components and shorter time-scale variation, and the difficulty of constraining large spatial scales using current data. However, they are often adopted as valuable independent data for validating assimilation results (section 2.4).

The drastic decrease of observations from the TAO array started from 2012. In August 2013, the distribution of data from the TAO array became very sporadic in the central and eastern equatorial Pacific. In contrast, the data from floats seem to be distributed densely enough to partly compensate for the decrease of TAO data. Figure 1 compares equatorial Pacific temperature anomaly fields among the objective analysis of the TAO/TRITON data produced by the NOAA/ Pacific Marine Environmental Laboratory (PMEL) (http://www.pmel.noaa.gov/tao/jsdisplay/; accessed 20 May 2015) and the operational DA results of NCEP (Behringer and Xue, 2004), JMA (Fujii *et al*, 2012), ECMWF (Balmaseda *et al*, 2013a), and ABoM (Yin *et al*, 2011). Figure 1 shows an increased diversity among the objective analyses (both with and without an ocean model) in 2013 compared to those in 2010, in part due to the lack of TAO array data to constrain the systems. In 2010, all results show a similar anomaly pattern that is typical for the La Niña period. In contrast, assimilation results in 2013 indicate different longitudes for the position of the eastern tip of the warm anomaly, a feature which ENSO forecasters particularly focus on in order to judge the possibility of emergence of the anomaly at the surface. Moreover, the objective analysis field is most doubtful due to the small number of available data, which makes it difficult for ENSO forecasters to use in verification of their forecasts. Figure 1 suggests that the TAO array data along the Equator provide indispensable information for SIDA systems. Further studies are needed to determine how

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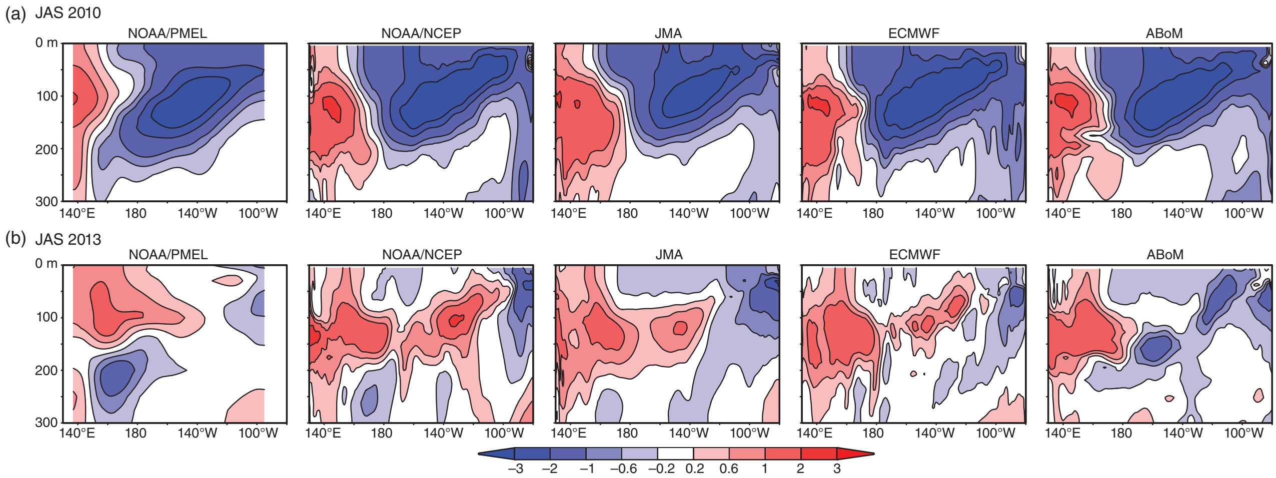

Figure 1. Temperature anomaly (°C) distribution averaged over (a) July–September 2010, and (b) July–September 2013 in the equatorial vertical section in the Pacific in the objective analysis from the TAO/TRITON data produced by PMEL and the operational DA results of NCEP, JMA, ECMWF, ABoM. The anomaly is calculated as the deviation from the WOA09 for the objective analysis, and those from the monthly climatology of each system in 1989–2007 for the DA results.

representative this case is and to derive a more robust result. To assess the impacts of missing TAO data on uncertainties of subsurface temperature analyses from operational SIDA systems, several operational centres have started routine near-real-time intercomparison of the tropical Pacific subsurface temperature fields (at the experimental web page hosted by NCEP: http://www.cpc.ncep.noaa.gov/products/GODAS/multiora_body.html; accessed 20 May 2015; accessed 20 May 2015). The representativeness of the case above is expected to be clarified through this project.

2.2. Short-to-medium range ocean forecasting

The launch of the TOPEX/Poseidon altimeter satellite in 1992 brought substantial information on variability of western boundary currents and mesoscale eddies, which can be used for monitoring/forecasting them. Subsequently, a variety of ocean DA systems for short-to-medium range ocean forecasting (hereafter, OFDA systems) have been developed in operational centres and research institutes in several countries. The Global Ocean Data Assimilation Experiment (GODAE, 1998–2008) and its follow-on program, GODAE Ocean View (2009-present), have supported these developments over the last 15 years.

The OFDA systems operated by centres such as Mercator (Lellouche *et al*, 2013), the Canadian Meteorological Centre (Smith *et al*, 2013b), UKMO (Blockley *et al*, 2014), US Navy (section 3.2.2), and ABoM (Oke *et al*, 2008; 2013; Brassington *et al*, 2012), include the tropical Pacific in their target domain. Those OFDA systems generally assimilate all sources of *in situ* temperature and salinity data including those observed by TAO/TRITON array and ARGO floats, and SST and SSH from satellites in their eddy-permitting/resolving ocean models (typically 1/4° to 1/12° horizontal resolution). A variety of assimilation schemes (OI, 3D-Var, EnOI, Ensemble Kalman Filter (EnKF), SEEK filter, etc.) are used in those systems. Most OFDA systems are forced by sea surface fluxes estimated by atmospheric DA systems. Typically, forecasts of 5 days to 1 month are performed routinely with those systems. Most OFDA systems serve as the backbone for a variety of applications of ocean security, search and rescue, monitoring of marine ecosystems, etc. A couple of OFDA systems also provide the ocean initial conditions for coupled models in S-I forecasting. Retrospective ocean DA runs or reanalyses are often performed with OFDA systems (and SIDA systems) for validation of the system.

OFDA systems require TAO/TRITON data, as well as ARGO profiles, for constraining the ocean heat content, stratification and circulation in the Tropics. However, observations with a higher spatial resolution than that of current *in situ* observing systems are preferable for those systems because they are generally designed to reproduce the variability associated with mesoscale eddies, and because the eddy activities (e.g. TIWs, the Mindanao eddy, etc.) are very vigorous in the northern tropical Pacific. This requirement is partly satisfied by satellite observations of SSH and SST, but they are still not sufficient. It is also important to note that most OFDA systems do not use sub-daily high-frequency measurements of TAO/TRITON array but assimilate daily mean profiles of the temperature and salinity measurements. Recently, several institutes also direct their efforts toward developing a coupled DA and prediction system based on OFDA and atmospheric numerical weather prediction (NWP) systems for improving short- to medium-range forecasting of the atmosphere and ocean, especially coupled phenomena such as tropical cyclones and the Madden-Julian oscillation (MJO).

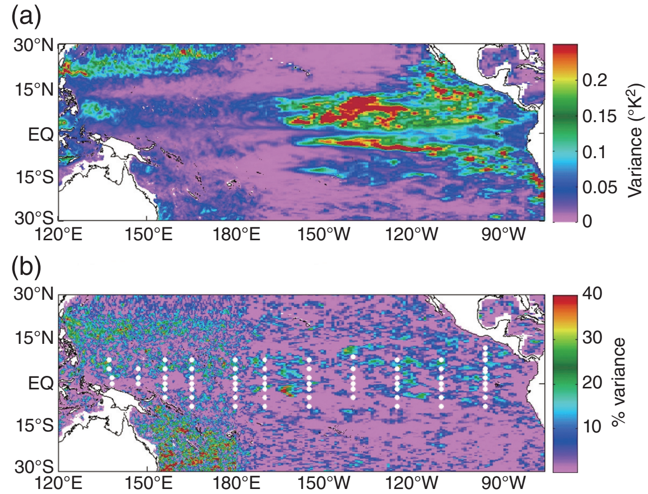

Figure 2. (a) Time-averaged variance of 100 m depth temperature among 0–3-day lead-time forecasts from different ensemble members. (b) The percentage reduction in the time-averaged variance shown in (a) compared with the time-averaged variance of 100 m-depth temperature among 4–7-day lead-time forecasts (equivalent to the background field for the data assimilation). The positions of the mooring buoys constituting the TAO/TRITON array are superimposed. The variance is calculated from the lagged ensemble assimilation and prediction runs of OceanMAPS. The averaging is performed from 1 March to 31 August 2012.

In Figure 2, we show the ensemble spread of data-assimilated fields and its prediction mode error growth in the operational Ocean Modelling, Analysis, and Prediction System (OceanMAPS) of ABoM (Brassington *et al*, 2012; Brassington, 2013) as an example of the current status of OFDA. OceanMAPS implements a four-member lagged ensemble data assimilation run where each member is initialized using observation data every 4 days, and the timings of the initialization lagged 1–3 days behind those for other members. A 12-day prediction run (including 5-day

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hindcast) is also performed from the initialized fields of every ensemble member. The horizontal resolution of the system is 0.1° × 0.1° for the region 90°E–180° and 75°S–20°N, and 0.1° × 0.9° for the central and eastern tropical Pacific east of 180°.

Uncertainty of 100 m depth temperature in the system is large in the eastern tropical and far-western tropical Pacific, and relatively small between 140°E and 170°W (Figure 2(a)). This error distribution is similar to the distribution of the climate variance of temperature at this depth. Figure 2(b) indicates the percentage reduction in the uncertainty of the initialized field compared with the background hindcast. The percentage reduction is large at points where data assimilation substantially constrains the ocean state. Large error reduction values are concentrated east of Australia and in the zonal band between 15 and 20°N west of 180°, but large reduction values are also interspersed in the area covered by the TAO/TRITON array, especially in the western Pacific between 0 and 10°N and the NINO-3 region (90°W-150°W; 5°S- 5°N).

Areas where the percentage reduction is large are collocated with the moored buoys, indicating that temperature observations from buoys are essential for constraining the ocean state in OceanMAPS.

2.3. *Ocean state estimations*

The development of *in situ* and satellite observing systems, such as those under the global XBT (expendable bathythermograph) program, the Tropical Ocean-Global Atmosphere (TOGA)-TAO Program, the World Ocean Circulation Experiment (WOCE), and satellite observing systems (especially altimetry such as the TOPEX/Poseidon), have spurred the efforts of ocean state estimation (a term used here to include ocean reanalysis) for climate research. The Climate Variability and Predictability (CLIVAR) Program of the World Climate Research Programme (WCRP) has been fostering such efforts under the Global Synthesis and Observations Panel (GSOP; Lee *et al*, 2009; Balmaseda *et al*, 2015). In addition to ocean state estimation based on model-data synthesis, there are also observation-based analyses of temperature and salinity at monthly and longer temporal resolution.

The first decade-long reanalysis of the global ocean to facilitate the study of the prediction of seasonal-interannual variability was produced by the NOAA Geophysical Fluid Dynamics Laboratory (GFDL; Rosati *et al*, 1995). Since then other ocean reanalysis products have been developed to understand and monitor the ocean climate variability. Some of them are produced by model-based SIDA/OFDA systems at operational centres such as ECMWF (Balmaseda *et al*, 2013a), NOAA/NCEP (Xue *et al*, 2011), and Mercator (Ferry *et al*, 2012). These historical reconstructions help to understand and monitor the ocean climate variability (e.g. Xue *et al*, 2012; Balmaseda *et al*, 2013b). In addition, the research community has also developed some ocean reanalysis products, for example, the Simple Ocean Data Assimilation (SODA) analysis (Carton *et al*, 2000), and those produced under the EU project Enhanced Ocean Data Assimilation and Climate Prediction (ENACT; Davey *et al*, 2006).

Reanalyses are generated by repeating short-term DA cycles, and thus physical consistency is not guaranteed across the short-term cycles. In contrast, the Estimating the Circulation and Climate of the Ocean (ECCO) Consortium, formed in 1998 as part of the WOCE synthesis activity, have been producing dynamically consistent estimates of the ocean state and surface fluxes (e.g. Stammer *et al*, 2002), satisfying the conservation laws described by the underlying models, through Kalman filtering and 4D-Var. The K-7 Consortium in Japan has also continued a similar effort through 4D-Var (Masuda *et al*, 2003, 2010). Ocean state estimation products (including reanalyses) have been applied to various topics of oceanographic research, including sea level variability (e.g. Wunsch *et al*, 2007), water-mass pathways (e.g. Fukumori *et al*, 2004), the subtropical cells in the Pacific (e.g. Lee and Fukumori, 2003), mixed-layer heat balance (e.g. Kim *et al*, 2007), estimating surface fluxes and river runoff (e.g. Stammer *et al*, 2004), and interannual and decadal variability of the ocean heat content (e.g. Xue *et al*, 2012; Balmaseda *et al*, 2013b).

Recently, weakly coupled assimilation efforts have been made by some institutes such as JMA/Meteorological Research Institute (MRI; Fujii *et al*, 2009, 2011) and NCEP (Climate Forecast System Reanalysis, CFSR; Saha *et al*, 2010; Xue *et al*, 2011). These efforts assimilate atmospheric and oceanic data in the atmosphere and ocean models separately (or more simply, assimilate oceanic data in the ocean model alone), but use the coupled model to communicate the influence of the observations through the exchange of first-guess fields instead of simultaneous assimilation of atmospheric and oceanic data in the coupled models. Nevertheless, the use of ocean and atmospheric data from *in situ* (e.g. the TAO/TRITON array) and satellite systems has improved some aspects of the estimation compared to the stand-alone atmospheric and ocean estimation. For example, Wen *et al* (2012) showed that the weakly coupled assimilation in CFSR results in a more realistic representation of the atmospheric and oceanic signature of TIWs in the Pacific, which is a coupled ocean-atmosphere feature. A fully coupled ocean-atmosphere DA effort was made by Japan's K-7 group (Sugiura *et al*, 2008), showing an impact on the hindcast of the 1997/98 El Niño, and by GFDL (Ensemble Coupled Data Assimilation, ECDA; Zhang *et al*, 2007; Chang *et al*, 2013).

In situ temperature and salinity profiles and SSH data derived from satellite altimetry are assimilated in most ocean state estimations. The application requires particularly high-quality observations that permit systematic errors to be minimized together with accurate representation of the uncertainties associated with both the data and the model in order to detect small climate signals. Observing systems stably sustained for a long period are also desirable for long-term ocean state estimation because changes in observing systems induce temporal discontinuities in the estimated ocean fields.

TAO/TRITON mooring data provide valuable long time series and are an important constraint for this application. The multiple-parameter measurements of oceanic and atmospheric variables by the tropical mooring arrays have been important in the evaluation of the ocean state estimation systems and the corresponding heat budget analysis. As the community is moving towards coupled data assimilation, the ocean and surface meteorology measurements from the tropical mooring array will become more and more important.

2.4. *Decadal predictions*

Long time series of physically well-balanced ocean states are also necessary for 'decadal' predictions, which focus on time-scales of several years to a few decades. Decadal prediction, in which a CGCM is initialized using observation-based information and integrated for a decade, is included in the Coupled Model Intercomparison Project phase 5 (CMIP5) protocol (Taylor *et al*, 2012) and results are evaluated in the Intergovernmental Panel on Climate Change (IPCC) fifth assessment report (AR5). The feasibility of decadal predictions over the North Atlantic, and their relationship with the Atlantic Meridional Overturning Circulation (AMOC) have been investigated (e.g. Dunstone and Smith, 2010; Pohlmann *et al*, 2013a). Successful decadal prediction for the Pacific Decadal Oscillation (PDO), and the recent hiatus in surface warming have also been reported (e.g. Mochizuki *et al*, 2010; Guemas *et al*, 2013).

Relatively low resolution (1° horizontal) is usually adopted for the ocean part of a CGCM in decadal prediction systems. One strategy for initializing the ocean part of the CGCM is to force the ocean model variables toward independently analyzed ocean fields, including ocean reanalyses and other ocean state estimations, usually by nudging. Some systems also

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force atmospheric variables toward an atmospheric reanalysis. This strategy can be considered as a simple version of coupled data assimilation in the sense that coupled model dynamics are used to propagate the information of ocean and atmospheric data within the coupled model. In this strategy, the analysis fields are often used in the form of anomalies and so the method is called the 'anomaly initialization method' compared to initialization using full-valued fields. Feasibility of extending the SI forecasts to a decadal lead time, in which ocean observations are directly assimilated into the ocean part of the forecasting model by the SIDA system, has been explored in several studies (e.g. Doblas-Reyes *et al*, 2011), as well as decadal predictions initialized by a fully coupled ocean-atmosphere DA (e.g. T. Mochizuki, 2014; personal communication). What strategy is most effective for decadal forecasts is currently a subject of active research (e.g. Magnusson *et al*, 2013; Smith *et al*, 2013a). Although most decadal prediction systems are developed and exploited in research mode, UKMO has implemented decadal predictions operationally using the 'DePreSys' system (Smith *et al*, 2007).

In situ temperature and salinity profiles are utilised directly or indirectly in most decadal predictions, and long time series of data provided by TAO/TRITON buoys are important for this application. The requirements of decadal applications are similar to those for ocean state estimations. In particular, decadal predictions need to detect small climate signals, and therefore require accurate observation data. Sustained *in situ* measurements have been essential to evaluate model predictions of decadal changes such as PDO and the recent warming hiatus to understand the physical processes associated with the changes. Expansion of accurate observations in the deep ocean is also desirable for this application (e.g. Deep Argo).

2.5. Use of TAO/TRITON for validation

TAO/TRITON data are regularly used for calibration of DA systems, including SIDA and OFDA systems and those for climate research. Figure 3 shows an example of validation using TAO data for the temperature field in a reanalysis using the operational near-global ocean DA system in JMA (Fujii *et al*, 2012). It should be noted that the TAO data are assimilated in the reanalysis and are therefore not independent. Figure 3 indicates that temperature at 60 m depth has relatively large errors compared with that at 10 and 120 m depths at 0°N–110°W. It also indicates the existence of a cold bias at 10 and 60 m depths after 2000. Appearance of this bias may be caused by a qualitative change of wind stress forcing fields provided by the atmospheric DA system. It also shows that the temperature at 120 m depth deviates considerably from the observation data around the periods of the strong El Niños in 1997/98 and 2009/10, probably because the model cannot represent the large variations associated with those events. This kind of information cannot be obtained without comparing the simulation fields with a long time series observation record. Therefore the long time series provided by TAO/TRITON moorings are extremely valuable to validate long-term simulations such as ocean reanalyses which cover several decades and include interannual variability of the tropical ocean.

The TAO current data are also often exploited for validation although they are assimilated in few ocean DA systems. Figure 4 shows an example from Mercator. The representation of the Equatorial Undercurrent (EUC) was a known weakness in version 2 of the global 1/4° system operated by Mercator for MyOcean, the European project providing products and services for all marine applications (http://www.myocean.eu; accessed 22 May 2015; accessed 22 May 2015). To assess the improvement of EUC in the version 3 of the system, the analyzed zonal velocity profiles were compared with the current measurements at TAO buoys. Both versions of the system use a static SEEK filter (Lellouche *et al*, 2013 give a description of the system configurations). The figure

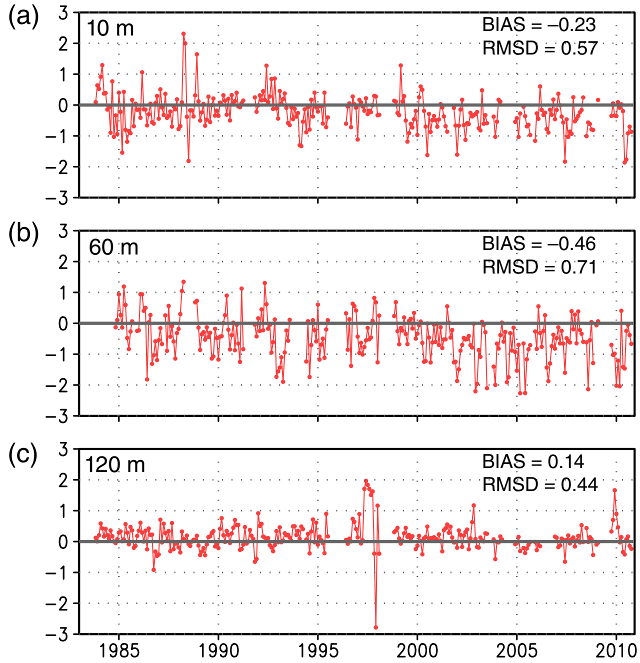

Figure 3. Time series of the difference (°C) between temperature in the reanalysis using the JMA operational near-global ocean DA system and that obsevred by a TAO mooring at (a) 10, (b) 60 and (c) 120 m depths at 0–110°W between 1983 and 2010. The mean difference (BIAS) and RMSD are shown at the top-right corner of each panel.

demonstrates that the EUC in the version 3 system is strengthened and agrees with the TAO measurements much better than that in the version 2 system. This improvement is attributed to the use of a more realistic mean dynamical topography and its error statistics applied for assimilation of the along-track SSH data in the version 3 system. Thus the TAO current data are valuable as independent data for validating ocean DA fields.

3. Observing system evaluations

3.1. Evaluation for seasonal-interannual forecasting

3.1.1. Observing system experiments (OSEs) at NOAA (NCEP and GFDL)

The Climate Program Office of NOAA called for a coordinated OSE at NCEP and GFDL to assess impacts of TPOS for S-I forecasting. At NCEP, the operational seasonal forecast model, referred to as Climate Forecast System version 2 (CFSv2) (Saha *et al*, 2013) is used. Although the operational version of CFSv2 is initialized by a weakly coupled ocean and atmosphere reanalysis (sections 2.1 and 2.3), this was not done for the OSE project discussed here. Instead, the global ocean data assimilation system (GODAS; Behringer and Xue, 2004) was used to assimilate ocean-only data. *In situ* temperature and salinity profiles are assimilated in the reference run and the model SST is nudged strongly to the NOAA daily optimum interpolation SST (OISST; Reynolds *et al*, 2007). GFDL uses the ensemble coupled data assimilation (ECDA) system (Zhang *et al*, 2007). In ECDA an ensemble-based filtering algorithm is applied to the GFDL's fully coupled climate model, CM2.1, which is one of two GFDL CMIP3 models (Delworth *et al*, 2006). *In situ* temperature and salinity profiles, winds, sea level pressure and temperature data from the NCEP reanalysis 2 (Kanamitsu *et al*, 2002), and a weekly version of Reynold's OISST are assimilated in the reference run.

To assess the relative roles of the TAO/TRITON and Argo data in constraining the upper ocean thermal structure and improving ENSO forecasts, four OSE runs were performed. The four runs and their designations include:

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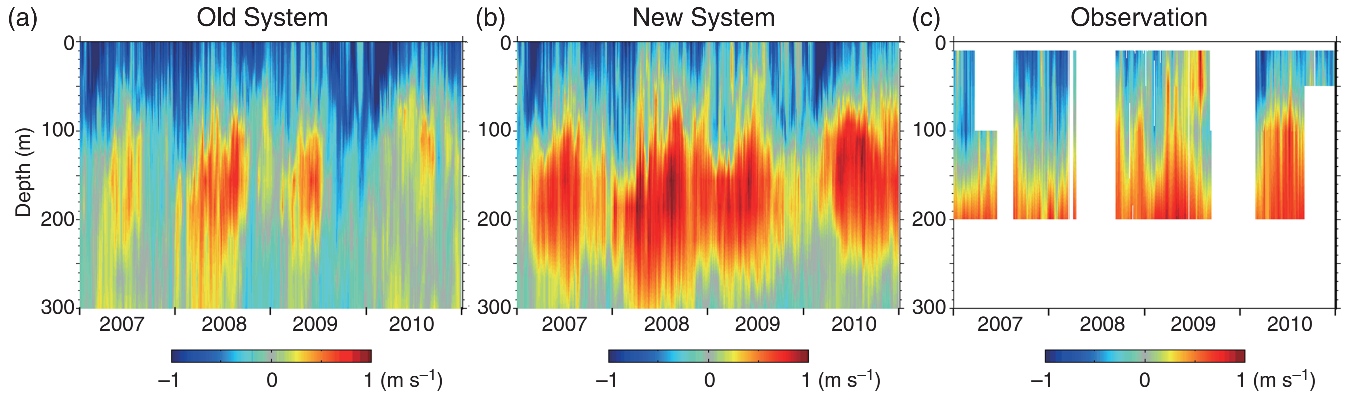

Figure 4. Comparison of the evolution of the currents (m s^{-1}) at 0–165°E for the (a) old and (b) new global 1/4° system at Mercator with (c) the TAO mooring data.

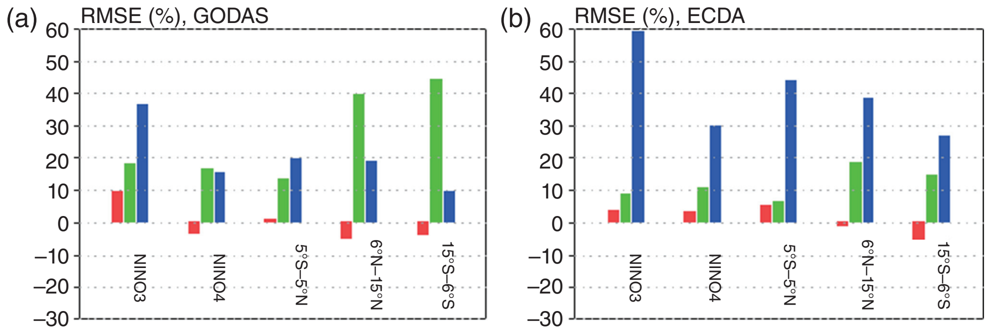

Figure 5. Impacts on RMSE of SSH anomalies in 2004–2010. Shown are RMSE difference normalized by RMSE of ALL for (a) GODAS and (b) ECDA. Red - noMoor minus ALL (impacts of Mooring bouys); Green - noArgo minus ALL (impacts of Argo); Blue - CTL minus ALL (impacts of all *in situ* profiles).

CTL: no ocean profiles assimilated,
ALL: all ocean profiles assimilated,
noMoor: all ocean profiles assimilated except the mooring profiles,
noArgo: all ocean profiles assimilated except Argo.

The model SSH from each OSE run is validated against independent satellite altimeter SSH observations. The impacts of assimilation of the various combinations of ocean observations are quantified using Root Mean Square Error (RMSE) against satellite altimetry SSH anomalies. Figure 5 indicates that the impacts of moorings (red bar) are generally weak. The moorings improve RMSE by 10% in NINO-3 of GODAS and by 3–5% in the equatorial indices of ECDA. In contrast, the impacts of Argo (green bar) are much larger. Argo improves RMSE by 15–19% in GODAS and 8–11% in ECDA. In off-equatorial regions, the impacts of Argo are strongly positive. The impacts of all *in situ* profiles (blue bar) are strongly positive in all areas. The results suggest that *in situ* ocean observations are absolutely critical in constraining model errors in the entire tropical Pacific, and it is mostly critical in the eastern Pacific (NINO-3 region). RMSE in NINO-3 is reduced by 37% in GODAS and 60% in ECDA. Smaller impacts of Argo than those of all *in situ* data in the equatorial regions in ECDA implies that TAO/TRITON data themselves are sufficient to constrain oceanic fields in the system. The reason of the poor performance of GODAS in NINO-4 (160°E-150°W; 5°N-5°S) and the off-Equator regions (negative impacts of moorings and smaller impacts of all *in situ* data than those of Argo alone) is discussed in Xue *et al* (2015).

In order to evaluate the impacts of *in situ* observations on the skill of hindcasts, hindcast experiments were initialized from the four OSEs around 1 January, 1 April, 1 July and 1 October during 2004–2011. From each start time, an ensemble of 6 (10) coupled forecasts with perturbed initial conditions was integrated up to 12 months ahead using CFSv2 (CM2.1). The monthly forecast SSTs were first smoothed with a 3-month running mean. SST anomalies were then derived by removing the model climatology calculated separately for each initial month and lead month in 2004–2011. The hindcast skill was measured by RMSE against the weekly OI SSTs that were calculated for all initial months and all years, but for lead months from 0 to 4 (L0–4) and from 5 to 9 (L5–9) separately.

Although Figure 6 indicates that several impacts of observation data on seasonal forecast skills are negative, the impacts of TAO/TRITON on the skill of equatorial Pacific SST are consistently positive in both models (red bars). The RMSE is reduced by 5–15% in equatorial SST indices (NINO-3, NINO-4, NINO-3.4 (170-120°W; 5°N-5°S) and tropical Pacific (TPAC; 20°S–20°N, 120°E–80°W)) in both models. Argo data are beneficial too, but the amplitude of RMSE reduction is smaller than TAO/TRITON, except in NINO-4. The moorings also have positive impacts on the tropical Indian and Atlantic Oceans and the main developing region (MDR; 10–20°N, 80–20°W) for L5–9, and Argo floats have positive impacts on those regions for both L0–4 and L5–9 in CFSv2. Impacts of the moorings and Argo on those regions are not clear in CM2.1.

Model drift is still very large (not shown), which may diminish the benefits of all *in situ* profiles in some cases (blue bars). For CFSv2, the model drift varies considerably with initial times, so it is hard to remove model systematic bias. For CM2.1, both the model drift and the impacts of *in situ* profiles on hindcast skill are strong functions of initial months; impacts can be positive, neutral or negative depending on the initial month. We conclude that model drift is a big obstacle for models to fully utilize the benefits from all *in situ* profiles.

3.1.2. *Observing system experiments at JMA/MRI*

JMA/MRI also conducted a series of OSEs to evaluate the relative impact of Argo floats and TAO/TRITON buoys on the ocean DA fields and ENSO forecasts using an operational seasonal forecasting system (Fujii *et al*, 2011, 2015). The system uses the nearly-global ocean DA system, MOVE-G (Multivariate Ocean Variational Estimation System Global Version; Fujii *et al*, 2012), for the ocean initialization, in which a multivariate 3D-Var scheme

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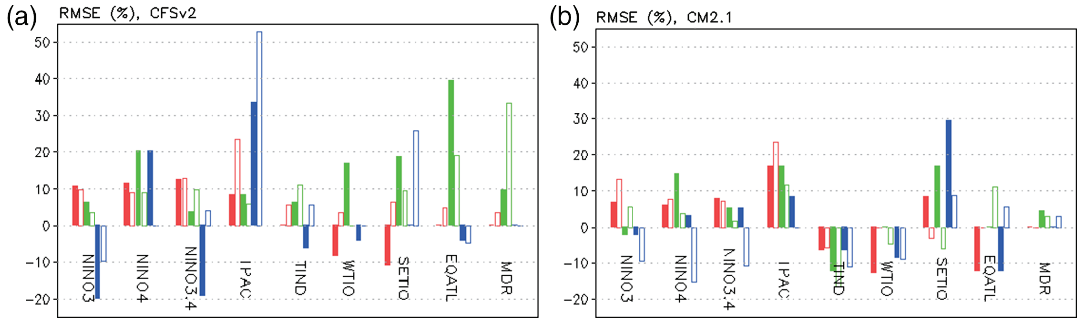

Figure 6. Hindcast skill of RMSE difference normalized by RMSE of ALL for (a) CFSv2 and (b) CM2.1 for various SST indices. Red bar - noMoor minus ALL; Green bar - noArgo minus ALL; Blue bar - CTL minus ALL. Filled (unfilled) bars are skill for L0–4 (L5–9). The RMSE are calculated with seasonal mean SST anomalies between model and observations in the period of 2004–2011 for all initial months and lead month L0–4 and L5–9 separately. RMSEs are calculated for NINO-3, NINO-4 (5°S–5°N, 160°E–150°W), and NINO-3.4 (5°S–5°N, 170–120°W) regions, tropical Pacific (TPAC; 20°S–20°N, 120°E–80°W), tropical Indian (TIND; 20°S–20°N, 30–120°E), western tropical Indian (WTIO; 10°S–10°N, 50–70°E), and south eastern tropical Indian (SETIO; 10°S–0°, 90–110°E) Oceans, equatorial Atlantic (EQATL; 5°S–5°N, 70°W–30°E), and Main Developing Region (MDR; 10–20°N, 80–20°W).

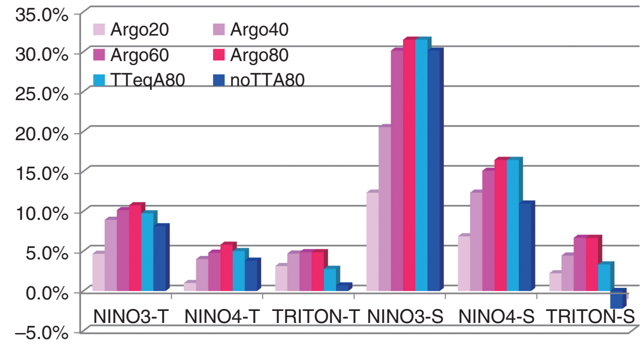

Figure 7. Reduction of the RMSE of the 0–300 m averaged temperature (T) and salinity (S) averaged over NINO-3, NINO-4, and TRITON (5°S–5°N, 120–160°E) regions in OSEs at JMA/MRI with respect to the RMSE of noArgo, and normalized by the RMSE of noArgo. The RMSEs are calculated for the period of 2004–2010.

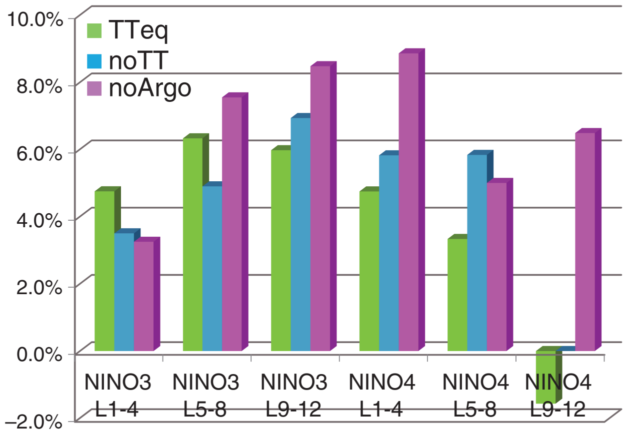

Figure 8. Increase of the RMSE of the NINO-3 and NINO-4 SST indices in the hindcasts from TTeq, noTT, and noArgo at JMA/MRI with respect to the RMSE in the hindcasts from ALL, and normalized by the RMSE in the hindcasts from ALL for L1–4, L5–8, and L9–12. Forecast biases are estimated for each lead month and for each OSE separately, and removed from the forecasted values.

assimilates satellite SSH, gridded SST, and *in situ* temperature and salinity profiles, including data from Argo, XBT, and tropical moorings.

Impacts of TAO/TRITON and Argo data on the ocean heat content in the equatorial Pacific in the DA system is quantified using seven OSE runs, namely, noArgo (the same as in 3.1.1), Argo20, Argo40, Argo60, Argo80 (20, 40, 60, 80% of Argo data and all available data from other than Argo are assimilated), noTTA80 (TAO/TRITON data and 20% of Argo data are withheld), and TTeqA80 (TAO/TRITON data outside 2.5°S–2.5°N and 20% of Argo data are withheld). The accuracy of these runs is evaluated by the RMSE against the 20% of Argo float profiles that are withheld from all OSE runs (Figure 7). This figure clearly demonstrates that the impact of Argo data on salinity is larger than that on temperature. The impact of Argo is largest in the NINO-3 region and smallest in the TRITON region. It also indicates that the accuracy monotonically improves with an increasing number of assimilated Argo floats from 0 to 80% for both temperature and salinity in NINO-3 and NINO-4 regions, indicating that any further increase in the number of Argo floats has the potential to further improve the accuracy of the DA system in those regions. The accuracy of the run without TAO/TRITON (noTTA80) is roughly similar to the ARGO40 run in NINO-3 and NINO-4 regions, implying impacts of TAO/TRITON is similar to 40% of Argo data. It should be noted that we evaluated here the impacts of TAO/TRITON complementary to all other available data, including Argo and altimetry data, and that the intrinsic impact of TAO/TRITON is larger (Fujii *et al*, 2015). Accuracy of the salinity field is not degraded if data from extra-equatorial buoys outside of 2.5°S–2.5°N are withheld (TTeqA80) in the two regions, although assimilation of extratropical buoys has some impacts on temperature there. The impact of TAO/TRITON data is as large as (larger than) that of 80% of Argo data in the TRITON region, and the data from extra-equatorial buoys also have some impact.

We also quantified the impact of TAO/TRITON and Argo data on the forecasts of NINO-3 and NINO-4 SST indices using four OSE runs, namely, ALL, noArgo (the same as in 3.1.1), noTT (TAO/TRITON data are withheld), and TTeq (TAO/TRITON data outside of 2.5°S–2.5°N are withheld). We performed 13-month, 11-member ensemble hindcasts from each OSE run using the coupled model. The hindcasts were started from the end of January, April, July, and October in 2004–2011. TAO/TRITON data reduce the RMSE of the NINO-3 and NINO-4 indices for lead months from 1 to 4 (L1–4) by 3.5 and 5.8%, respectively (Figure 8). The impact on NINO-3 increases for lead months from 5 to 8 (L5–8) and from 9 to 12 (L9–12). In contrast, the impact on NINO-4 is not changed for L5–8 and disappears for L9–12. Assimilating equatorial buoy data (2.5°S–2.5°N) alone (TTeq) increases the RMSEs by 3–6% compared to ALL, except for NINO-4 for L9–12. It should be noted that the RMSEs in TTeq are larger than noTT for NINO-3 for L1–4 and L5–8, which may indicate the importance of assimilating equatorial and extra-equatorial (outside of 2.5°S–2.5°N) buoys simultaneously, especially for relatively short-lead-time forecasts of the NINO-3 index. Impacts of Argo are larger than those of TAO/TRITON on both NINO-3 and NINO-4 for all lead times except for NINO-3 indices for L1–4 and NINO-4 for L5–8. The impact of Argo on NINO-3 is enhanced with increasing lead time, but for NINO-4 the impact is not monotonic being smaller for L5–8 than for shorter and longer lead times.

Although this study has evaluated the impacts of TAO/TRITON and Argo data through OSEs, it should be noted that the error statistics and MDT used in the DA process of MOVE are also estimated from *in situ* observations. Impacts of *in situ*

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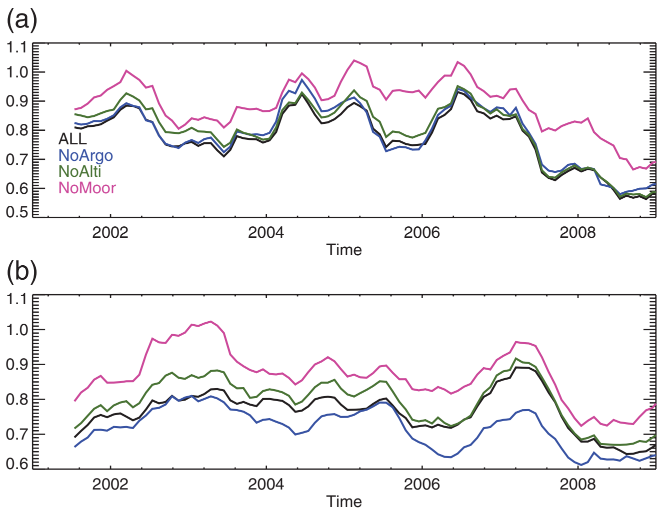

Figure 9. Time series of the temperature fit to moorings measured as the RMSE between each OSE at ECMWF and the mooring observations in the depth range 100–150 m over the regions (a) eastern Pacific (90–130°W, 5°S–5°N), and (b) western Pacific (150°E–190°W, 5°S–5°N).

TAO/TRITON and Argo data are thus underestimated here because their contributions through the statistics and MDT are not considered in the evaluation.

3.1.3. *Observing system experiments at ECMWF*

A series of OSEs has been performed using the ECMWF's ocean reanalysis system (ORAS4; Balmaseda *et al*, 2013a), which is used to initialize the operational monthly and seasonal forecasts. Here, we introduce the results of four OSE runs, i.e. ALL, noMoor, noArgo (the same as in 3.1.1) and noAlti (SSH data are withheld).

Figure 9 presents the time series of the RMSE between all OSEs and the mooring observations around the thermocline (where the maximum impact is observed) of the eastern (90–130°W, 5°S–5°N) and western (150°E–190°W, 5°S–5°N) equatorial Pacific. The statistics are the average RMSE over 10-day forecasts. Therefore, the mooring observations have not been assimilated yet (except for the bias correction, described below), and thus could be considered as independent data. As expected, in both areas the agreement with the mooring data is poorest when the mooring data are withdrawn. Withdrawing the altimeter also degrades the consistency with the mooring data. Withdrawing Argo has a neutral impact in the eastern Pacific, but, surprisingly, reduces the RMSE in the western Pacific. This may be caused by the different spatial sampling of the mooring and TAO data. It can also be due to the inability of the DA to blend them adequately (for instance, by not having adequate spatial decorrelation scales or representativeness error). Further work is needed to disentangle these two possibilities by, for instance, checking if this is a common feature in other DA systems, and if it is the case in model-independent evaluation. When computing the fit with respect to all *in situ* observations (and not only data from moorings), the fit to *in situ* temperature profiles is degraded in the eastern tropical Pacific whenever any data type is withheld (not shown). This indicates that all data types help improve the state estimate from the data assimilation system.

However, it should be noted that all experiments with the ECMWF system adopt a bias correction scheme, which applies corrections to temperature, salinity and, in the equatorial wave-guide, to the pressure gradient. The mean seasonal cycle of the bias correction is estimated *a priori* from a previous DA experiment using all *in situ* observations, and therefore the above OSEs still implicitly include information from all observing systems on the ocean mean state. A supplemental run assimilating all data without the bias correction indicated that the bias correction has the largest impact, illustrating the role of the observations in correcting the mean. As mentioned earlier, some *in situ* and satellite data are used in deriving the MDT. But the OSEs results presented here do not account for the contributions of these data to the MDT that was assimilated as part of the SSH assimilation. Balmaseda and Anderson (2009) show that the indirect impact of the *in situ* data through the MDT can be as large as the direct impact measured by the data retention experiments in the previous ECMWF operational system.

Although the initial conditions from ALL, noArgo, noAltim and noMoor have been used to initialize seasonal forecasts, using the current operational ECMWF seasonal forecasting system S4, it was not possible to measure a significant contribution of individual observing systems. This is contrary to the results reported by Balmaseda and Anderson (2009), who used a similar methodology to evaluate the impact of the observing system in the previous ECMWF operational seasonal forecast system S3. They found that all the observing systems contributed to the skill of ENSO prediction. The reasons for the lack of impact are under investigation. Possibilities include: (i) a too limited sample in a forecasting system with large ensemble spread; or (ii) the impact of the observing system in the mean state through the bias correction is not accounted for.

3.1.4. *Evaluation using common metrics*

Results of OSEs depend on the quality and characteristics of the ocean DA systems used as well as the forecasting model. Therefore it is desirable to examine the consistency among the results of OSEs in different centres. For this purpose, an evaluation of OSE results in NOAA (NCEP and GFDL), JMA/MRI, and ECMWF has been initiated intercomparison using common metrics. An example of the intercomparison is shown in Figure 10. This figure demonstrates substantial diversity of observation impacts among the four systems. However there are some common features. For example, the averaged RMSD of temperature between ALL and noMoor/noTT in 0–300 m is relatively large in the far western equatorial Pacific, and northeast of the Solomon Islands. These are regions where the model accuracy is relatively low. Differences are also large in the zonal band along 5°N particularly for the OSEs in NCEP and JMA/MRI, probably due to energetic eddy activity there. Through further examination we aim to estimate some general impacts of the observing system that do not depend strongly on the DA systems used and are thus likely to be more robust.

3.2. *Evaluation for short- to medium-range ocean forecasting*

3.2.1. *Near-real-time OSE (GODAE Ocean View OSEval Task Team initiative)*

Under GODAE Ocean View, the Observing System Evaluation (OSEval) Task Team has advocated the development and application of tools and techniques that quantify the impact of ocean observations on OFDA systems. It has also encouraged studies that evaluate observational impacts on SIDA systems and ocean state estimations for climate research (e.g. Oke *et al*, 2009, 2015), and thus supported studies shown in this article. The team also intends to issue observation impact statements that provide feedback and requirements to observation agencies through evidence of the impacts of the observations, mainly on operational systems.

In order to achieve routine monitoring of current observing systems, the OSEval Task Team plans to set up near-real-time (NRT) OSEs. These consist of the nominal operational forecast system and a second system where a single observation component of the observing system is withheld. By comparing the results of the run excluding a particular observation with the operational run, the impact of the withheld observation type on the forecast system is assessed. NRT OSE experiments were performed in

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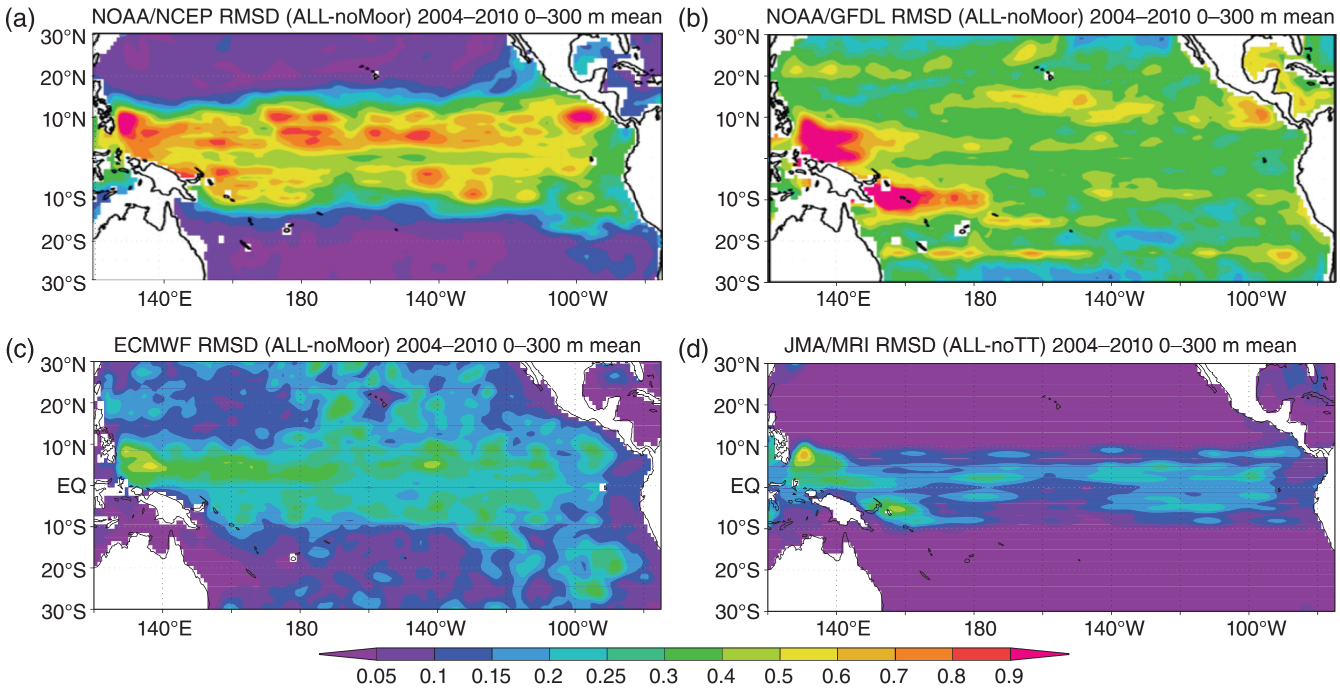

Figure 10. RMSD of temperature (°C) between ALL and noMoor (noTT for JMA/MRI) averaged over 0-300 m depths. The statistics are calculated over 2004-2011 for (a) NCEP and (b) GFDL, and over 2004-2010 for (c) ECMWF and (d) JMA/MRI. For JMA/MRI, noTT is used instead of noMoor because noMoor is not performed in JMA/MRI.

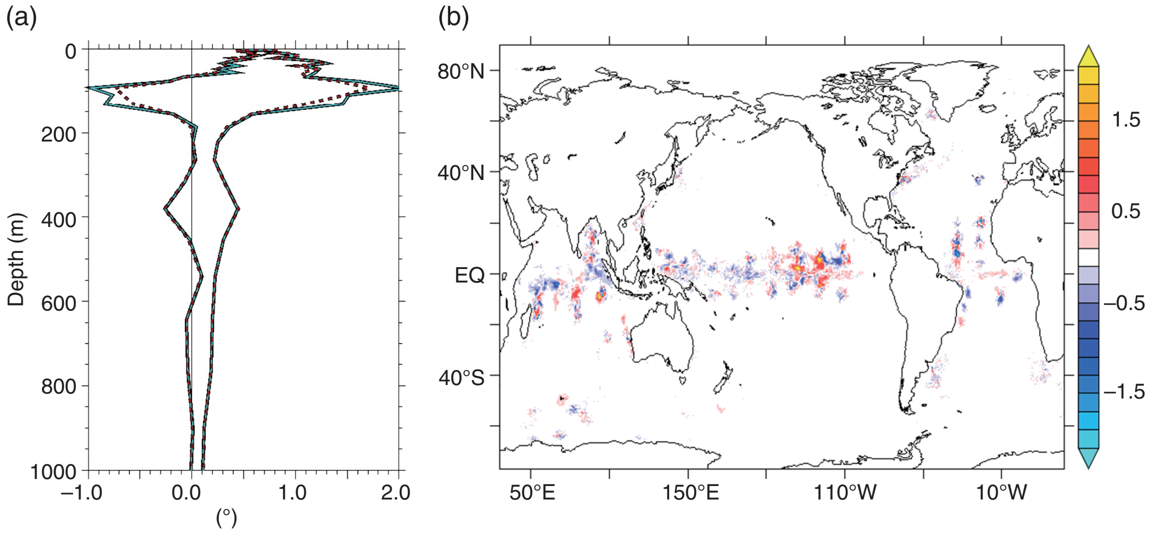

Figure 11. Results from NRT OSEs at Mercator. (a) Mean and RMS observation-analysis error to *in situ* temperature observations in the NINO-3 region with the TAO assimilated (red), and not assimilated (blue). (b) Temperature differences at 100 m depth on the last day of the 1-month experiments with and without TAO observations assimilated.

2011 with the UKMO's operational ocean forecasting system (Lea *et al*, 2014).

Following this GODAE Ocean View initiative, NRT OSEs were also conducted over successive months of year 2013 by Mercator. During March 2013, temperature and salinity profiles from the tropical moorings (including those in the Atlantic and Indian Oceans) are withheld from assimilation in a simulation. All the other *in situ* observations, satellite SSH data and SST maps are assimilated as usual. In another simulation, all *in situ* observations are assimilated as well as satellite SSHs and SSTs. The real-time ocean analysis and forecasting system used for those simulations is based on a 1/4° global ocean model configuration and described in Lellouche *et al*, (2013). A 3D temperature/salinity bias correction computed with *in situ* model-observation misfits available three months prior to the analysis is applied below the thermocline. The effect of withholding a part of the *in situ* dataset can then be underestimated for simulations shorter than three months due to the memory of this bias correction.

Different observation-based statistics and ocean state quantities are compared between the two simulations to evaluate the impact of withholding data from the tropical moorings. Statistics of the temperature difference between the simulations and *in situ* observations (including those made by TAO/TRITON) are computed over the month for both simulations. Misfits for the tropical moorings are included. Figure 11(a) shows the profiles of the mean and RMS temperature misfits in the NINO-3 region. The higher level of errors, RMS and mean differences, are found at the thermocline depth, which is shallower when going eastward. The assimilation of the TAO observation reduces the RMS difference and bias (mean difference) of temperature by about 15% at that depth. Under the thermocline, the bias correction is still active and takes into account innovations from the previous two months.

Figure 11(b) shows the temperature differences at 100 m depth on the last day of the one-month experiments. Important differences are visible at and around the moorings and can reach 2 °C. Salinity differences are found within the thermocline and

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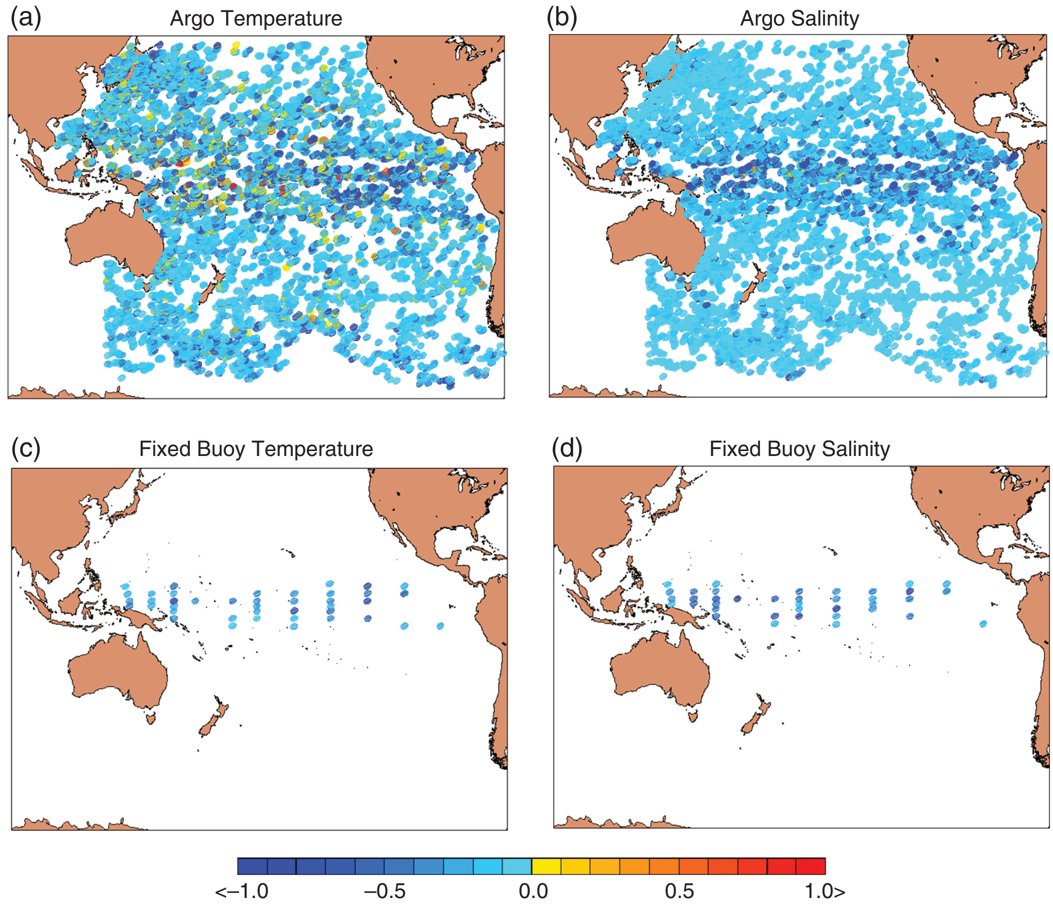

Figure 12. Observation impact on 48 h forecasts of (a,c) temperature and (b,d) salinity observations by (a,b) Argo floats and (c,d) fixed buoys assimilated in global HYCOM. Magnitude of the forecast error reduction (increase) from assimilation of the observation is shown as a negative (positive) value. Each point represents the combined impacts of all depth-level observations in the vertical profile. Units are °C and PSU. Adjusted from Cummings and Smedstad (2014).

can reach 0.5 PSU at the surface (not shown). After one month, changes have already propagated away from the mooring points through ocean tropical dynamics. The SST data prevent larger differences in temperature close to the surface, but the surface salinity is much less constrained by data assimilation. The number of salinity data is also much smaller than the temperature data from TAO moorings. These results are generally consistent with Lea *et al* (2013).

Further investigation and longer simulations will be required to fully assess the impact on the analysis and forecast of the 1/4° global ocean of the assimilation of the temperature and salinity data from the tropical mooring arrays because TAO data return was already low in 2013; a year prior to 2011 should be chosen to have a higher return data rate. The results highly depend on the assimilation system, the physical model and observation error *a priori* specification. Those quantities are not always well known. One month does not allow a full assessment of the observation impact but does give some indication.

3.2.2. *Evaluation of forecast sensitivities using an adjoint model*

Assessment of the contribution of each observation assimilated by the Navy Coupled Ocean Data Assimilation (NCODA) 3D-Var (Cummings and Smedstad, 2013) on the forecast performance of global Hybrid Coordinate Ocean Model (HYCOM; Bleck, 2002) with a resolution of 1/12° around the Equator is achieved by the adjoint-based observation sensitivity technique (Langland and Baker, 2004; Cummings and Smedstad, 2014). The technique computes the variation in a measure of the forecast error due to the assimilated data through the adjoint of the assimilation system. An advantage of the adjoint method is that observation impact is estimated simultaneously for the complete set of observations assimilated. There is no need to selectively add or remove observations in the assimilation to estimate observation value as in an OSE. The procedure is therefore computationally inexpensive and can be used for routine observation monitoring. Results presented here are from the Pacific domain of global HYCOM cycling with NCODA 3D-Var using a 24 h update interval for the period 16 September to 30 November 2012. Because the data impacts have large day-to-day variability, the impacts from assimilation of individual observations are pooled within observing systems and geographic locations over the time period of the experiment.

Figure 12 shows the geographic variation of the impacts of assimilating Argo and fixed buoy (primarily TAO/TRITON) temperature and salinity profile observation data types on reducing HYCOM 48 h forecast error. The results shown here are the summed impacts of the separate depth-level observations in each vertical profile. In addition, each displayed point averages the impacts of multiple profiles from the same or different floats if, during the 2.5 month period of the study, more than one profile occurred within a HYCOM grid cell (∼7 km midlatitude). Note that the TAO/TRITON buoy observations are assimilated as daily averages of profiles reported almost hourly. Figure 12 indicates that the majority of temperature profile observations assimilated show beneficial impacts, although non-beneficial impacts are seen in some Argo float profiles. However, assimilation of salinity observations is always beneficial. Figure 13(a) presents the summed observation impacts for the different profile observing systems. The summations have been normalized by the number of observations to facilitate the intercomparison since temperature observations are dominated by synthetic temperature profiles derived from satellite SSH measurements and salinity observations are dominated by Argo. The results show that, on average, impacts of temperature and salinity from all observing systems are beneficial, with the most beneficial observing system assimilated

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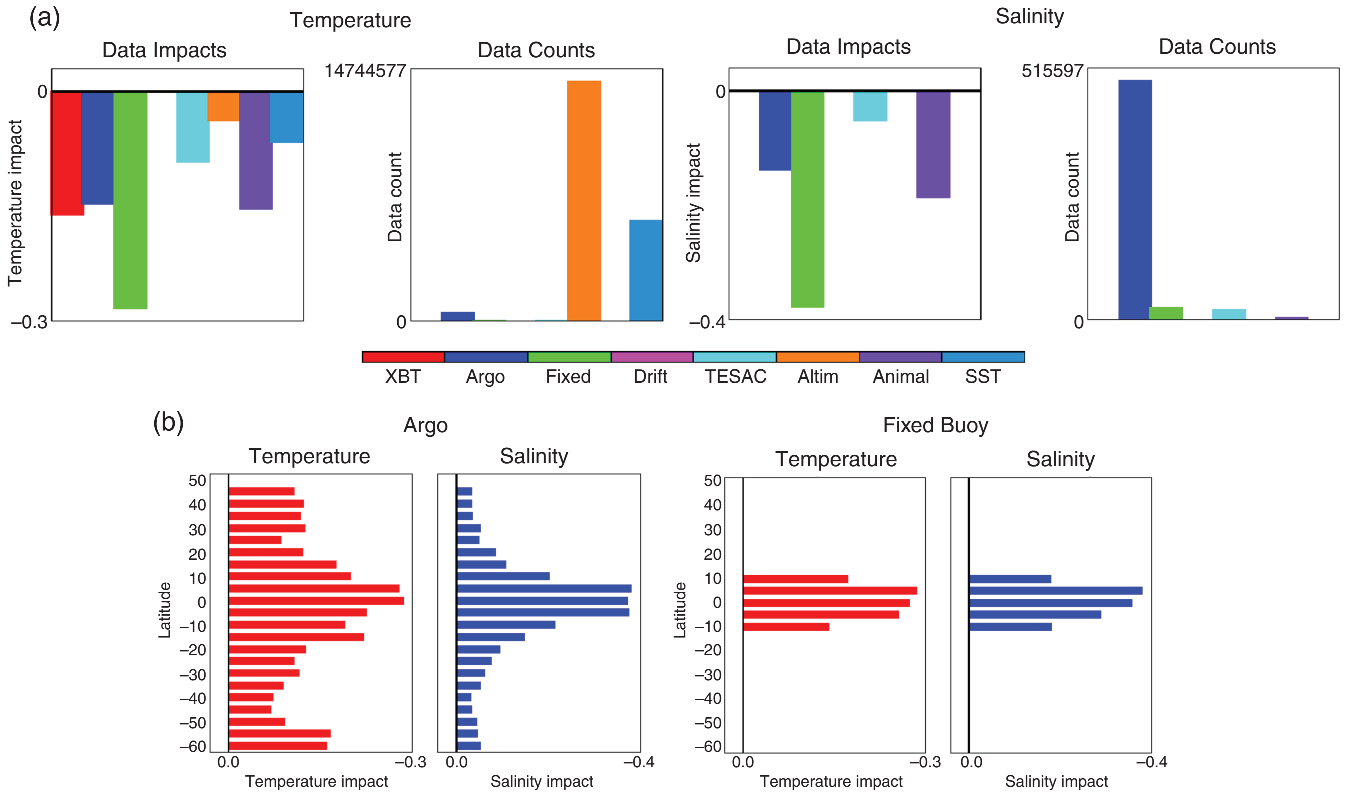

Figure 13. (a) Temperature (°C) and salinity (PSU) observation impacts assimilated in global HYCOM on 48 h forecasts normalized by the number of observations and partitioned by observing system. Includes all observations assimilated, i.e. XBT, Argo, Fixed Buoy (Fixed), Drifter (Drift), TESAC, synthetic temperature profiles derived from satellite SSH, animal sensor, and satellite SST retrievals. Negative data impact values indicate beneficial observing systems. (b) Per observation data impacts on 48 h forecasts of Argo and fixed buoy arrays for temperature (°C) and salinity (PSU) and partitioned by 5° latitude bands. Adjusted from Cummings and Smedstad (2014).

being the tropical fixed moorings. Figure 13(b) compares Argo and the fixed-buoy arrays as a function of 5° latitude bands on a per observation basis. The greatest impact of Argo is in the Tropics (±10° latitude), with impact magnitudes of Argo temperature and salinity similar to those of the tropical moorings at those latitudes.

It is shown that the greatest data impacts for reducing forecast error in the Pacific basin of global HYCOM are for observations in the Tropics. This result is an indication that HYCOM model errors are greatest in the tropical Pacific and that continued and routine observing is needed there to adequately constrain the model. On a per observation basis, the impact of Argo and the tropical fixed moorings are shown to be equivalent at low latitudes. Thus, the two observing systems can be considered to be complementary when initializing global HYCOM. The routine assimilation of observations from both Argo and TAO/TRITON work together to consistently reduce HYCOM 48 h forecast error for both temperature and salinity. Therefore, both observing systems are needed in the future.

3.3. *Evaluation for ocean state estimations*

Beside the fact that most of SIDA and OFDA are applicable to some ocean state estimation for climate research, we here focus on the 4D-Var systems which enable us to estimate a dynamically consistent ocean state, in particular over a long term (several months to several decades) in a single optimization (e.g. Stammer *et al*, 2002). The accuracy of such estimation at a specific time depends on various aspects of observed information, not only of that time but also of the past and future times within the assumed assimilation time window. In particular, a data synthesis system applying the smoothing scheme requires sustainable monitoring during the time window in order to obtain a suitable ocean climate state. Here, we show an application of adjoint sensitivity analysis (e.g. Fukumori *et al*, 2004) to ocean OSE (e.g. Köhl and Stammer, 2004).

A 4D-Var ocean-state estimation system with 1° × 1° resolution, developed as a part of the Japan Agency for Marine-Earth Science and Technology (JAMSTEC)–Kyoto University collaborative program (the K7 consortium; Masuda *et al*, 2003, 2010), is used to evaluate an ocean observing system for improved long-term ocean-state estimation. The adjoint model in the system is applied to identify the sensitivity of temperature at 100 m depth located along the Equator and some of the WOCE Hydrographic Program (WHP) lines in the Pacific basin to the retrospective ocean state estimation.

The sensitivity is here defined by $\nabla_{x(t)}J$, where J is the sum of water temperature T at location **r** arranged along the Equator and the WHP lines at intervals of 1° of latitude or longitude at 100 m depth at time t_f: $J = \sum_{\mathrm{r}=WHP} T(\mathrm{r}, t_f)$, $x(t)$ is water temperature field at retrospective time t. The obtained sensitivity values show possible contributions of the hydrographic observations along the lines to the retrospective state estimation. The sensitivity thus corresponds to the possible change in temperature taking place at the lines at an allocated model time (defined as year 0) when temperature changes at an arbitrary grid point at an arbitrary time in the past.

Figure 14(a) shows a vertical cross-section of the sensitivity in the equatorial region at −2 years. It is apparent that the sensitivity values of 100 m temperature changes are almost lost in the upper 100 m and mostly distributed in the lower part of the thermocline around 150 m. This is because mixed-layer dynamics dominate the changes in temperature above 100 m on time-scales less than 2 years in this central region. This implies that sustainable observations at 100 m along the Equator could be required for retrospective ocean-state reconstruction for relatively short-term climate change, and that a hydrographic observation at 100 m can contribute to better representation of the thermocline if a 2-year period is chosen for the assimilation window.

Here we assess a rate of decrease in the sensitivity values to make best use of repeat surveys. Figure 14(b) shows the

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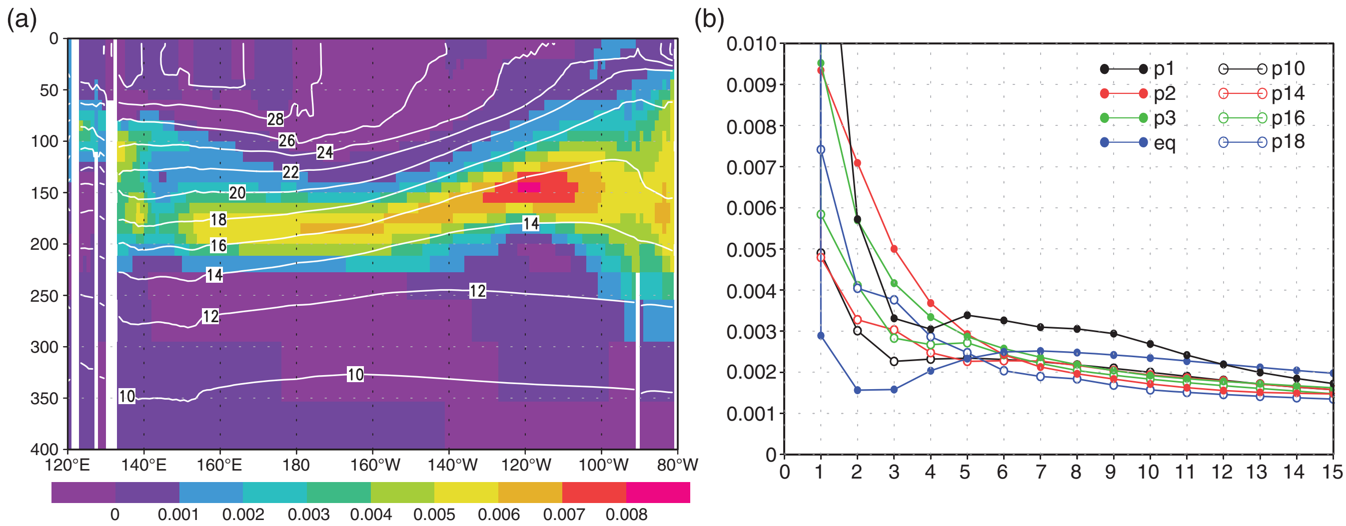

Figure 14. (a) Sensitivity of changes in water temperature (K, colour shading) at the WHP lines at 100 m depth in the Pacific Ocean in the vertical section along 0.5°N at −2 years in the JAMSTEC K7 system. The temperature (°C; white contours) of the background ocean state is superimposed. (b) Temporal evolution of the sensitivity averaged for each WHP hydrographic line at 100 m depth normalized to the initial value at year 0. The horizontal axis denotes the retrospective period from 0 to −15 years in reverse chronological order.

sensitivity values averaged within each hydrographic line at 100 m. These values show the impact of assumed observations at year 0 on the retrospective ocean state estimation within the lines at the depth when tracing back 15 years. The rate of decrease of the sensitivity during the retrospective period largely depends on the geographical location. The local memory of the ocean properties in equatorial region is shorter than that in other regions. By comparing the rates, we can quantitatively define the importance of the equatorial ocean as a key region to be intensively monitored. This kind of analysis enables us to provide unique information on the effectiveness of an ocean observing system on the retrospective ocean-state estimation. For example, in year 1 the rates of decrease of sensitivity for the equatorial line were 99.7% (Figure 14(a)). This shows observations obtained once a year are evaluated as low-impact ones on the long-term state estimation. These decreasing rates are thus considered to give a measure of the observational frequency of the system and also contribute to ocean observing system evaluations.

In the real ocean, mesoscale eddies and various small-scale fluctuations sometimes play a role in determining ocean properties. These influences can be evaluated by applying the adjoint approach to a higher-resolution model (e.g. Hoteit *et al*, 2010) or through ensemble sensitivity analysis (e.g. Torn and Hakim, 2008). A regional assimilation effort at SIO also aims to quantify the impact of moored observations of temperature, salinity, and velocity under the influence of mesoscale eddies using the ECCO adjoint (4D-Var) assimilation system (resolution 1/3 to 1/6°).

3.4. *Evaluation for decadal predictions*

Impacts of TPOS on decadal predictions have not been substantially evaluated yet since it is a relatively new science field. However, Doblas-Reyes *et al* (2011) investigated impacts of ocean observation data on decadal predictions using a version of the ECMWF coupled forecast system. They performed three decadal hindcast experiments. The first one is not initialized. In contrast, the second and third ones are initialized using ocean observation data, although the correction of XBT bias proposed by Wijffels *et al* (2008) and Ishii and Kimoto (2009) is adopted only in the third one. Their Figure 5 shows improvement of prediction skill for 2–5 year lead time over the tropical Pacific by assimilating ocean observation data, which implies the importance of TPOS for decadal prediction. Furthermore, a substantial improvement was obtained by correcting XBT bias. This result indicates that the accuracy of ocean observation data is a crucial factor for decadal prediction.

More recently, Pohlmann *et al* (2013b) demonstrated improved decadal prediction skill over the equatorial Pacific in the first 3-5 years of the prediction by using ocean and atmosphere initialization, which is consistent with the result of Doblas-Reyes *et al* (2011) introduced above.

4. Summary

This article has introduced the current status of ocean DA systems used for a variety of applications and discussed their requirements for the TPOS including the TAO/TRITON array and Argo floats. It summarizes past and current studies to evaluate impacts of those observation data. It can be considered as background information which can guide the evaluation exercise of TPOS.

Temperature data from the TAO/TRITON array are assimilated in most ocean DA systems, and are generally considered to be essential for constraining the ocean heat content, stratification, and circulation in the Tropics in these systems. The intercomparison of the temperature fields along the Equator among the DA systems for Seasonal-to-Interannual (S-I) forecasting in NCEP, JMA, ECMWF, ABoM (Figure 1) reveals that the recent decrease of TAO/TRITON data may severely affect the accuracies of the analysed fields making it more difficult to issue reliable forecast statements, although the representativeness of this case should be evaluated in a further study. TAO/TRITON data are also shown to be essential for validating ocean DA products.

Most of the observing system evaluation studies shown in this article are based on data denial experiments (i.e. OSEs) within a given DA system. The results exhibit a known limitation of OSEs: evaluated impacts of observing systems depend strongly on the quality and characteristics of both the ocean DA systems and the forecasting model, and applications. In particular, current coupled models still have large errors and biases, and in the presence of model error observation impact results are difficult to interpret.

In spite of the limitations above, positive impacts of TAO/TRITON are demonstrated in most of the studies introduced in this article. Although the details of the impacts depend on the study, the TAO/TRITON impacts are generally similar to and sometimes larger than the impacts of Argo in the equatorial Pacific. The complementary aspects of the tropical mooring and Argo data impacts suggest that the loss of TAO/TRITON data would not be compensated by Argo profiles. Therefore we conclude that a further loss of TAO/TRITON data

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will lead to a further degradation of the forecast skill in the tropical Pacific and will have a follow-on detrimental impact on many applications based on ocean DA systems.

Here we should note another limitation of the observing system evaluation experiments described in the article. The experiments only evaluated the impacts of the ocean observations from TAO/TRITON. The surface meteorological data routinely collected from TAO/TRITON moorings have not been evaluated by the ocean data denial experiments. For example, de Boisséson *et al* (2014) indicated the importance of wind data from the TAO/TRITON array for reconstructing the recent increasing tendency of the thermocline slope in the equatorial Pacific. Thus, evaluation through OSEs in which only the tropical mooring temperature and salinity data are withheld are important, but the OSEs will underestimate the impact of the complete TAO/TRITON array, which routinely reports observations for more ocean and atmospheric variables in the coupled system.

Most studies introduced here demonstrate the importance of Argo floats. The evaluation through OSEs in JMA/MRI further indicates that an increase in the number of Argo profiles would improve the accuracy of state estimates by ocean DA systems. Enhanced deployment of Argo float has now started along the Equator in the Pacific. Although this article summarizes the positive impacts of TAO/TRITON on ocean DA systems and ocean model forecasts, it will need updating given the ongoing recovery of the mooring array and the increase in the equatorial Argo coverage from the use of floats with Iridium communication.

Continued deployment and maintenance of the tropical mooring arrays in all of the ocean basins is highly desirable. However, given funding constraints, a re-prioritization of the design of the mooring arrays might be appropriate and timely, taking into account the complementarity of other observing systems such as Argo. This effort should be aided by an internationally coordinated multi-model effort in (tropical) observing system evaluation and design. The recent crisis of the TAO array provides the rationale for commencing new studies in evaluating the tropical Pacific observing system. Follow-up of these studies will be carried out by the GODAE Ocean View OSEval task team.

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