White Paper #5 – Evaluation of the Tropical Pacific Observing System from the data assimilation perspective

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1. Introduction

Ocean Data Assimilation (DA) systems are tools to synthesize ocean observation data using the numerical ocean models, and widely applied as the primary method for transforming the data into information which can be used effectively by society. Conversely, the capacity of ocean DA systems inevitably depends on the extent to which the observing system satisfies the requirements of the DA systems. If an observing system does not satisfy these requirements, the system cannot provide effective information to society, which implies observational data are abandoned without being converted into effective information. Thus, it is essential for observing systems to satisfy the requirements of the DA systems. Moreover, quantifying the impacts of observational data on products of the systems is equivalent to evaluating the impact of the observations on society.

This white paper introduces the current status and achievement of ocean DA systems using the Tropical Pacific Observing System (TPOS), and summarizes requirements of the DA systems for the TPOS and the impacts of TPOS on the products of the systems. In this paper, we mainly focus on observations of physical parameters for the ocean interior, that is, temperature, salinity, and current velocity (including at the surface), and SSH because ocean DA systems generally calculate the time-evolution of those parameters. Although atmospheric observations at the surface affect ocean DA systems since they are often employed for estimating the atmospheric forcing data for the systems, we leave most discussions on those data to the white paper led by TPOS WP4. The white paper led by Mathis discusses on biogeochemical observations (TPOS WP6).

The purposes of ocean DA systems can roughly be classified into three categories. The first purpose is for ENSO monitoring and Seasonal-to-Interannual (S-I) forecasting, the second is for short-to-medium range (generally less than 1 month) ocean forecasting, and the third is for climate research, including estimations of the ocean state and variability in the climate time-scale and decadal predictions. In this paper, we discuss the current status and requirements of ocean DA systems, and impacts of the observations on those systems associated with each purpose separately, although many systems are being used for multiple purposes and over multiple time scales.

This paper is organized as follows. First, we introduce the current status and achievements 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, achievements, and requirements

2.1 Seasonal-interannual forecasting

Ocean DA systems as well as a Coupled ocean-atmosphere General Circulation Model (CGCM) are essential components of general S-I forecasting systems in operational centers 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 centers for monitoring equatorial wave activity, variability of the equatorial thermocline, and other oceanic phenomena associated with ENSO.

Deployment of TAO array under the Tropical Ocean and Global Atmosphere (TOGA) program initially realized the operational monitoring of the ocean interior state in the equatorial Pacific using ocean DA systems in the early 1990s (e.g., Ji et al., 1995). In this early stage, the DA systems assimilated temperature profiles alone. Assimilation of SSH data started in the mid 1990s after the launch of the TOPEX/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 T-S) balance relationship (summarized in Fujii et al., 2011).

Current SIDA systems in operational centers generally use Ocean General Circulation Models (OGCM) 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, however, has started to use 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. 2014). The majority of the systems currently apply 3DVAR assimilation schemes (e.g., NCEP, JMA, and ECMWF). However, other sophisticated assimilation schemes are also used in other institutes (e.g., EnOI is adopted in ABoM; Yin et al., 2011). Although most systems are forced by sea surface fluxes estimated from atmospheric DA fields which are separately calculated, 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 SST in the ocean DA fields also affects atmospheric DA results (Saha et al., 2010). Development toward coupled DA has also started in other centers. Retrospective long-term (typically 20-30 years) ocean DA runs are often performed with SIDA systems in operational centers for validation and calibration of SI forecasting systems, and called “reanalyses”. This 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 (see subsection 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 Niños and La Niñas, and directly affect the atmospheric global circulation and climate. SIDA systems generally use SST data whose resolution and sampling intervals are typically 1˚ and 1 day. This resolution and interval generally seems to be sufficient for reconstructing the variability associated with ENSO. Horizontal distribution of SST is effectively 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 operation centers (see Cronin et al., 2014, TPOS WP10).

Assimilation of subsurface temperature observations is also essential for ENSO monitoring and S-I forecasting because variations of thermocline depths are considered to 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 Niños and La Niñas. 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. The meridional interval is smaller due to the stretched structure of waves in the zonal direction, but it is still not so demanding. The TAO/TRITON array was originally designed considering these requirements, and 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 the thermocline depth accurately. Considering the typical vertical resolutions of SIDA systems, a vertical interval around 10 m is desirable. In contrasts, the sampling interval of TAO/TRITON array in the temporal direction (1 hour) is very short compared to the time scale of target phenomena. Time-averaging is often performed before assimilating 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 utilized in current SIDA systems.

Temperature profiles observed by Argo floats, which are also major components of data assimilated into SIDA systems, complement the TAO/TRITON data. These have higher vertical and zonal resolutions (1 m, and 300 km), and their temporal sampling interval is reasonable for ENSO. However, the meridional sampling interval is somewhat larger than TAO/TRITON array, and currently few floats stay in the vicinity of the equator due to the equatorial divergence of the near surface current. Argo floats are, thus, less suitable than TAO/TRITON array for detecting the baroclinic wave activities along the equator (see TPOS WP10 for ARGO floats with improved equatorial performance).

Variability of the thermocline depth can be also detected by SSH observations, and therefore the majority of SI systems assimilate SSH data from satellites. The sampling interval across the SSH satellite paths is 100-300 km (the interval along the paths is much smaller) and the temporal interval is 10-40 days. These intervals seem to be reasonable for detecting ENSO-scale variability. However, the impacts of assimilating SSH is generally small because the information from SSH observation duplicates that from subsurface temperature data by TAO/TRITON and Argo floats, and because the complicated vertical structure in the equatorial region makes it difficult to infer the vertical distribution of the temperature anomaly from SSH that offers vertically integrated information on the temperature field alone. Assimilation of altimeter SSH needs support from sub-surface temperature and salinity profiles.

Considering the possibility that Tropical Instability Waves (TIW) and other 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 resolution may have some potential. Although the high resolution data cannot be employed for the current lower resolution SIDA systems, it could be better exploited with the use of higher resolution ocean models (a resolution of 1/4˚ is the target for SI forecasts for 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 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 whose horizontal scale is 100-200 km. Vertical resolution is also insufficient for reproducing the influence of salinity fields on SST and near-surface temperature.

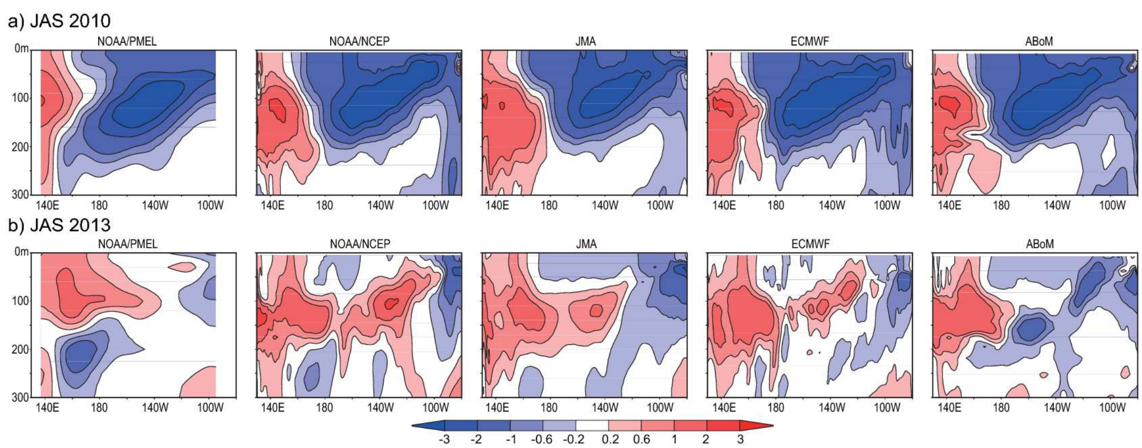

Figure 2.1 - Temperature anomaly (unit: ˚C) distribution averaged in a) July-September 2010, and b) July-September, 2013 in the equatorial vertical section in the Pacific in the objective analysis from the TAO/TRITON data produced by NOAA/PMEL and the operational DA results of NOAA/NCEP, JMA, ECMWF, 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.

Argo floats are powerful for observing salinity profiles. Their horizontal resolution is still insufficient, and the number of data is relatively low around the equator. But its vertically high-sampling profiles have substantial impacts on the reproduction of the salinity fields. SSH data also has 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). Assimilation of satellite SSS observation has started only recently and its impact is still being assessed. Although the accuracy of the SSS observations (more than 0.2 PSU for monthly mean) does not satisfy the requirements for DA (favorably less than 0.1PSU in 10-day mean), it may support the detection of the SSS variability associated with ENSO, and migration of the SSS fronts.

Data from ship observations are too sporadic spatially and temporally and cannot detect the basin-wide variability of the thermocline depth, nor the salinity fields. However, snapshots of the vertical section from the ship observation are useful to grab the image of the structures of temperature and salinity fields. These images promote our understanding and 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 controlling oceanic state by assimilating current data alone. However, they are often adopted as valuable independent data for validating assimilation results (see section 2.4).

The drastic decrease of observations from the TAO array started from 2011. In August 2013, the distribution of data from the TAO array becomes very sporadic in the central and eastern equatorial pacific. In contrast, the data from floats seems to be distributed densely enough to partly compensate the decrease of TAO data. However, Figure 2.1, in which the equatorial Pacific temperature anomaly fields are compared among the objective analysis from the TAO/TRITON data produced by NOAA/PMEL (http://www.pmel.noaa.gov/tao/jsdisplay/) and the operational DA results of NOAA/NCEP (Behringer and Xue, 2004), JMA (Fujii et al., 2012), ECMWF (Balmaseda et al., 2013a), and ABoM (Yin et al., 2011), shows the increased diversity among the objective analysis (without ocean model) and data assimilation results compared to those in 2010 resulting from the lack of TAO array data. In 2010, all results show similar anomaly pattern that is typical for the La Niña period. In contrast, assimilation results indicate different longitudes for the position of the eastern tip of the warm anomaly, 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. Thus the lack of TAO array data currently makes a tough situation for ENSO forecasters, which indicates that the TAO array data along the equator has indispensable information for SIDA systems. NOAA/NCEP, JMA, and ECMWF plan to start routine near-real time intercomparison of the tropical Pacific subsurface temperature fields from their operational SIDA systems, such as shown above currently.

2.1 Seasonal-interannual forecasting

The launch of the TOPEX/Poseidon satellite in 1992 realized the possibility of monitoring/forecasting variability of western boundary currents and meso-scale eddies by an ocean DA system. Subsequently, a variety of ocean DA systems for short-to-medium range ocean forecasting (hereafter, OFDA systems) have been developed in operational centers and research institutes in several countries. The implementation of GODAE (1998-2008) and its follow-on program, GODAE Ocean View (2009-current), underpin these developments in the last 15 years.

OFDA systems operated in some centers or groups, such as MERCATOR (Lellouche et al., 2013), the Canadian Meteorological Centre (Smith et al. 2013), UKMO (Blockley et al., 2013), US Navy (see sub subsection 3.2.2), and ABoM (Brassington et al., 2012), include the tropical Pacific in their target domain. Those OFDA systems generally assimilate 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, 3DVAR, EnOI, EnKF, etc.) are used in those systems. Most OFDA systems are forced by sea surface fluxes estimated by atmospheric DA system. 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 eco-systems, 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 for validation of the system, as well as SIDA systems.

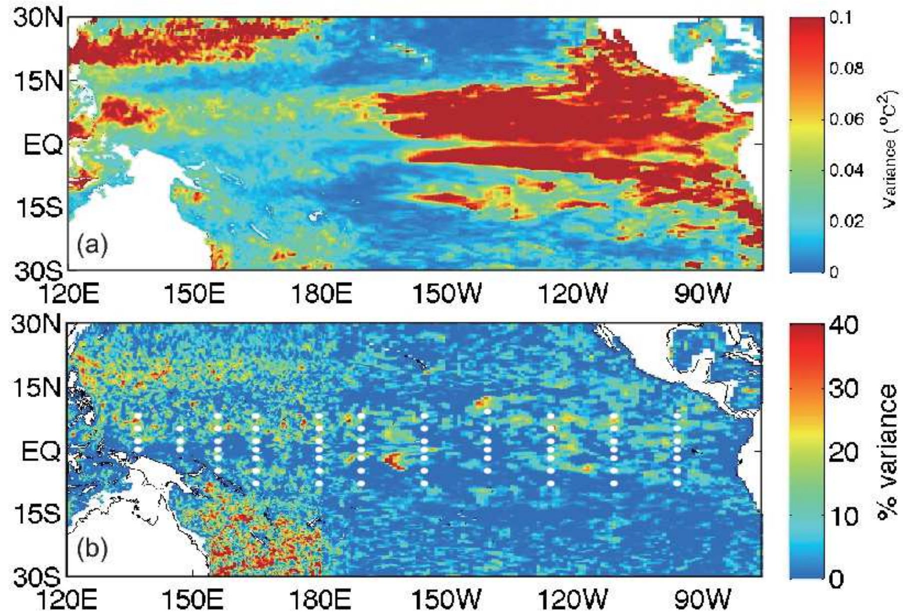

Figure 2.2 - (a) Time-averaged variance of 100-m-depth temperature among 0-3-day lead time forecasts from different ensemble members. (b) The percentage reduction in the time-averaged variance shown in (a) compared with the time-averaged variance of 100-m-depth temperature among 4-7-day lead time forecasts (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 for the period of from March 1st to August 31st in 2012 (adjusted from Brassington et al., 2014).

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 resolution than that of current in-situ observing systems seem to be favorable for those systems because they are generally designed to reproduce the variability associated with meso-scale eddies, and because the eddy activities (e.g., TIW, 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 fields 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 NWP systems for improving short-to-medium range forecasting of the atmosphere and ocean, especially coupled phenomena such as tropical cyclones and MJO.

In Figure 2.2, we show the uncertainty of data-assimilated fields and its growth in the prediction mode in the operational system in ABoM called OceanMAPS (Brassington et al., 2012, 2014; and Brassington, 2013) as an example of the current status of OFDA. OceanMAPS implements a 4-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 hindcast) is also performed from every 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 Pacific and also in the far-western tropical Pacific, and relatively small between 140°E and 170°W (Figure 2.2a). This distribution has a similarity with the distribution of the climate variance of temperature at this depth. The uncertainty is relatively high in the zonal band around 8°N due to activities of TIW. Figure 2.2b indicates the percentage reduction in the uncertainty of the initialized field compared with the background hindcast. The percentage reduction becomes large at points where data assimilation constrains the ocean state substantially. Large values are concentrated east of Australia and in the zonal band between 15-20° N west of 180˚, but also interspersed in the area covered by the TAO/TRITON array, especially in the western Pacific between 0°-10° N, and the NINO3 region. A closer look reveals that some areas where the percentage reduction is large are collocated with mooring buoys, which implies that temperature observations by the mooring buoys are essential for constraining the ocean state around there.

2.3 Ocean state estimations and decadal forecasts

The development of in-situ and satellite observing systems, such as those under the global XBT Program, the TOGA-TAO Program, the World Ocean Circulation Experiment (WOCE), and satellite observing systems (esp. altimetry such as the TOPEX/Poseidon), have spurred the efforts of ocean state estimation (a term used here loosely that includes the so-called ocean reanalysis) that gear towards climate research. NOAA GFDL first produced a decade-long reanalysis of the global ocean aiming to facilitate the study and prediction of seasonal-interannual variability (Rosati et al., 1995). A Simple Ocean Data Assimilation (SODA) system was developed (Carton et al., 2000) to produce a reanalysis of the (near) global ocean using historical data since 1960. The Estimating the Circulation and Climate of the Ocean (ECCO) Consortium, formed in 1998 as part of the WOCE synthesis activity, began to produce dynamically consistent estimates of the ocean state and surface fluxes (e.g., Stammer et al., 2002), satisfying the conservations laws described by the underlying models. The NOAA/GFDL effort (and the later NOAA/NCEP GODAE effort) has a tropical Pacific focus while SODA and ECCO have (near) global scope. There have been various efforts outside the US as well, including developments of reanalyses through SIDA and OFDA systems (See sub sections 2.1 and 2.2), for example, ECMWF (Balmaseda et al., 2013a), MERCATOR (Ferry et al., 2012) and CERFACS (Weaver et al., 2003) in France, INGV in Italy (Masina et al., 2011), and K-7 in Japan (Masuda et al., 2003). Ocean state estimation products 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., Balmaseda et al., 2013b).

Recently, weakly coupled assimilation efforts have been made by NOAA/NCEP (the CFSR, Saha et al., 2010). These efforts assimilate atmospheric and oceanic data in the atmosphere and ocean models separately but use the coupled model to communicate the influence of the atmospheric and oceanic observations through the first-guess field 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 the tropical instability waves 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 NOAA/GFDL (ECDA, Zhang et al., 2007; Chang et al., 2013).

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 CMIP5 protocol (Taylor et al., 2012) and the results are evaluated in IPCC 5th assessment report (AR5). The feasibility of decadal predictions over the North Atlantic, and the 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 are also reported (e.g., Mochizuki et al., 2010; Guemas et al., 2013).

Relatively low resolution (around 1°) is usually adopted for the ocean part of a CGCM used 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 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 is 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 are called "anomaly initialization method" compared to initialization using full fields. Feasibility of extending the SI forecasts, in which ocean observations are directly assimilated into the ocean part of the forecasting model by the SIDA system, to a decadal lead time is also explored in several studies (e.g., Doblas-Reyes et al., 2011), as well as initialization by a fully coupled ocean-atmosphere DA (e.g., Mochizuki, personal communication). Which strategy is most effective for decadal forecasts is currently a subject of active research (e.g., Magnusson et al., 2013; Smith et al., 2013). Although most decadal prediction systems are developed and exploited in research mode, UKMO has implemented decadal predictions operationally using the system named "DePreSys" (Smith et al., 2007).

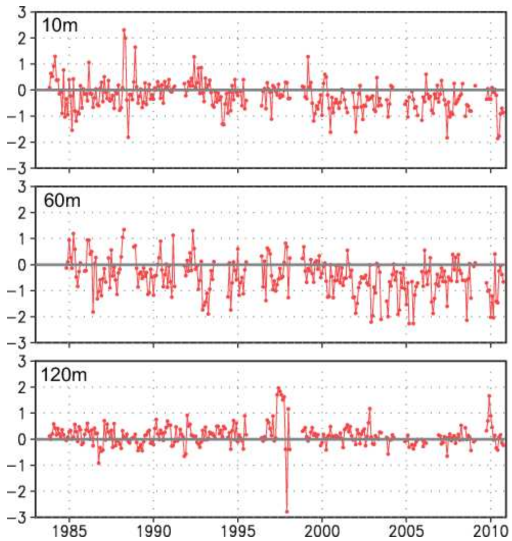

Figure 2.3 - Time series of the difference between temperature (°C) in the reanalysis using the JMA operational near-global ocean DA system and that observed by a TAO mooring at 10, 60 and 120 m depths at 0°-110°W between 1983-2010.

In-situ temperature and salinity profile data and sea level anomalies derived from satellite altimetry are assimilated in most ocean state estimations, and also utilized directly or indirectly in most decadal predictions. These applications require particularly accurate observation data in order to detect small climate signals. Observing systems stably sustained for a long period are also desirable for long-term ocean state estimation and decadal prediction because changes in observing systems induce temporal discontinuities in the estimated ocean fields and discrepancies in decadal prediction skill between the periods before and after the change. TAO/TRITON mooring data provide valuable long time-series and an important constraint for those applications. 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 Use of TAO/TRITON for validation

TAO/TRITON data are also regularly used for calibration of DA systems, including SIDA and OFDA systems and those for climate research. Figure 2.3 shows an example of validation using TAO data for the temperature field in a reanalysis using the operational near-global DA system in JMA (Fujii et al., 2012). Figure 2.3 indicates that temperature at 60 m depth has relatively large errors compared with that at 10 and 120 m depth at 0°-110° W. It also indicates 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 derivates considerably from the observation data around the periods of the strong El Niños in 1997-1998 and 2009-2010, probably because the model cannot represent large variations associated with the events. This kind of information cannot be obtained without comparing the simulation fields with a long time observation record. The long time series provided by TAO/TRITON moorings are, thus, extremely valuable to validate long-term simulations such as ocean reanalysis 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 2.4 shows an example in MERCATOR. The representation of the tropical currents is a known weakness in the old global 1/4° system in MERCATOR. To assess the improvement of the currents, the zonal velocity profiles in the old and new systems are compared with the current measurements at TAO bouys. The figure demonstrates that the zonal currents are strengthened and agree with the TAO measurements much better in the new system. The TAO current data are, thus, valuable as independent data for validating ocean DA fields.

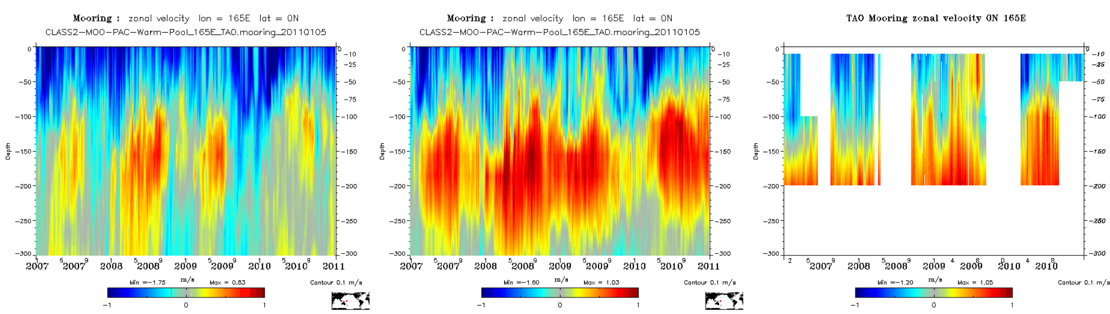

Figure 2.4 - Comparison of the evolution of the currents (ms^{-1}) at 0°-165°E for the old (left panel) and new (middle panel) global 1/4° system in MERCATOR with the TAO mooring data (right panel).

3. Observing system evaluations

3.1 Evaluation for seasonal-interannual forecasting

3.1.1 Observing system experiments 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 the 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 (see sections 2.1 and 2.3), for the OSE project discussed here, this was not done and an ocean-alone data assimilation system, referred to as global ocean data assimilation system (GODAS; Beheringer and Xue, 2004) was used instead. In-situ temperature and salinity profiles are assimilated in the reference run. The model SST is nudged strongly to the NOAA daily OI SST (Reynolds et al., 2007). At GFDL, an ensemble coupled data assimilation (ECDA) system (Zhang et al., 2007) was developed by applying an ensemble-based filtering algorithm 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, and the weekly 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, which assimilated (a) no ocean profiles (referred to as CTL), (b) all ocean profiles (the reference runs; referred to as ALL), (c) all ocean profiles except the mooring profiles (referred to as noMoor), and (d) all except the Argo profiles (referred to as noArgo). Since SSH observations are not assimilated in any OSE run, we use it to validate the model SSH. The impacts of ocean observations on SSH anomalies are quantified using RMSE against altimetry data. Figure 5 indicates that the impacts of moorings (red bar) are generally weak, and they improve RMSE by 10% in NINO3 of GODAS and by 3-5% in the equatorial indices of ECDA. In contrast, the impacts of Argo (green bar) are much larger. They improve 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 whole tropical Pacific, and it is mostly critical in the eastern Pacific (NINO3 region). RMSE in NINO3 is reduced by 37% in GODAS and 60% in ECDA.

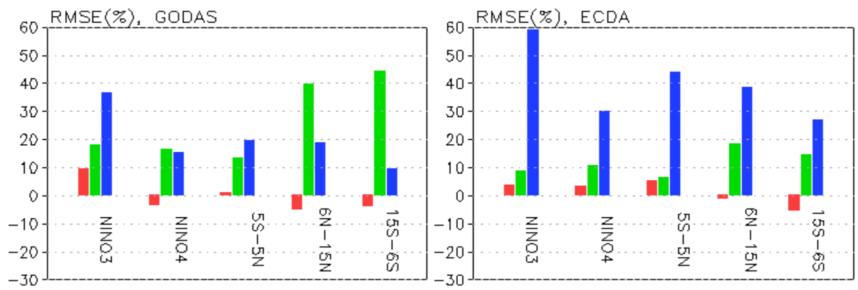

Figure 3.1 - Impacts on RMSE of SSH anomalies in 2004-2010. Shown are RMSE difference normalized by RMSE of ALL for GODAS (left) and ECDA (right). Red: ALL minus noMoor (impacts of Mooring bouys); Green: ALL minus noArgo (impacts of Argo); Blue: ALL minus CTL (impacts of all in-situ profiles).

In order to evaluate the impacts of in-situ observations on the skill of hindcasts, hindcast experiments were initialized from the four OSEs around January 1, April 1, July 1 and October 1 during 2004-2011. From each start time, an ensemble of 6 (10) coupled forecasts with perturbed initial conditions is integrated up to 12 months ahead using CFSv2 (CM2.1). The monthly forecast SSTs are first smoothed with a 3-month-running mean. SST anomalies are then derived by removing the model climatology calculated separately for each initial month and lead month in 2004-2011. The hindcast skill is measured by RMSE against the weekly OI SSTs that are calculated for all initial months and all years, but for lead months from 0 to 4 (L0-L4) and from 5 to 9 (L5-L9) separately.

The impacts of TAO/TRITON on seasonal forecast skill of equatorial Pacific SST are consistently positive in both models (red bars in Fig. 6). The RMSE is reduced by 10-25% in equatorial SST indices (NINO3, NINO4, NINO3.4 and TPAC) in both models. Argo data are beneficial too, but the amplitude of RMSE reduction is generally smaller than for TAO/TRITON. The moorings and Argo have the largest positive impacts on the eastern tropical Indian Ocean

(SETIO) SST in both models. The Argo has the largest positive impacts on the tropical Atlantic SST.

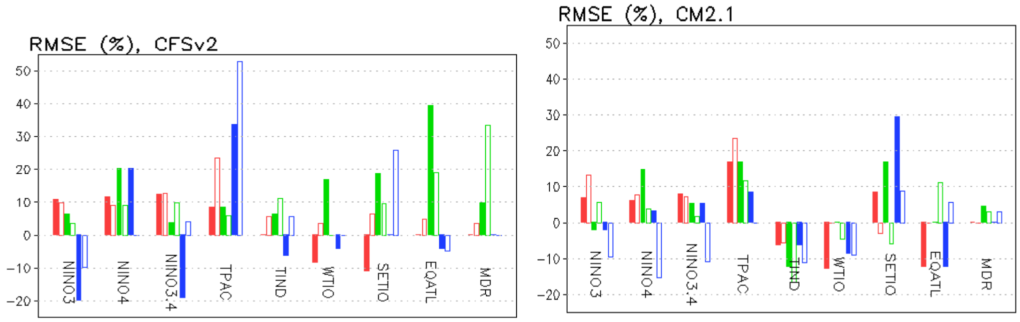

Figure 3.2 - Hindcast skill of RMSE difference normalized by RMSE of ALL for CFSv2 (left) and CM2.1 (right) for various SST indices. Red bar: ALL minus noMoor; Green bar: ALL minus noArgo; Blue bar: ALL minus CTL. Filled (unfilled) bars are skill for L0-L4 (L5-L9). The RMSE are calculated with seasonal mean SST anomalies between model and observations for all initial months, all years (2004-2011) and lead month L0-L4 and L5-L9 separately. RMSEs are calculated for NINO3 (5°S-5°N, 150-90°W), NINO4 (5°S-5° N, 160° E-150° W), and NINO3.4 (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).

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 initial months. We conclude that model drifts are still 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 and 2014). The system adopted the nearly-global ocean DA system, MOVE-G (Fujii et al., 2012), for the ocean initialization, in which a multivariate three-dimensional variational analysis scheme, MOVE, is employed to assimilate satellite SSH, gridded SST, and in situ temperature and salinity profiles, including data form Argo, XBT, and 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 out of 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 3.3). This figure clearly demonstrated that the impact of Argo data on salinity is larger than that on temperature. The impacts of Argo are largest in the NINO3 region and smallest in the TRITON region. It also indicates that the accuracy monotonically improves with increasing number of assimilated Argo floats from 0% to 80% for both temperature and salinity in NINO3 and NINO4 regions, indicating that any further increase in the number of Argo floats has the potential to further improve the accuracy of the DA system there. The accuracy of the run without TAO/TRITON (noTTA80) is roughly similar to the ARGO40 run in NINO3 and NINO4 regions, implying impacts of TAO/TRITON is similar to 40% of Argo data. Accuracy of the salinity field is not degraded even if data from extra-equatorial buoys outside of 2.5˚S-2.5˚N are withheld (TTeqA80) in the 2 regions, although those data have 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.

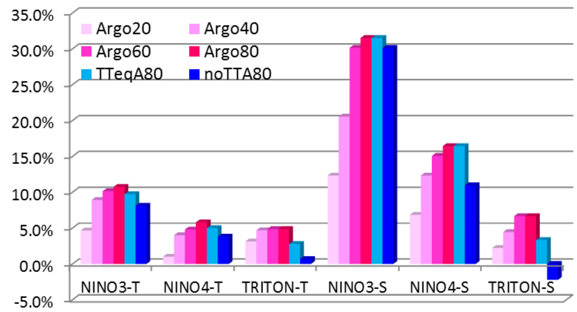

Figure 3.3 - Reduction of the RMSE of the 0-300m averaged temperature (T) and salinity (S) averaged in NINO3, NINO4, and TRITON (5˚S-5˚N, 120-160˚E) regions in OSE experiments from the RMSE of noArgo normalized by the RMSE of noArgo. The RMSEs are calculated for the period of 2004-2010.

We also quantified the impact of TAO/TRITON and Argo data on the forecasts of NINO3 and NINO4 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 reduces the RMSE of the NINO3 and NINO4 indices for lead month from 1 to 4 (L1-4) by 3.5% and 5.8%, respectively (Figure 3.4).

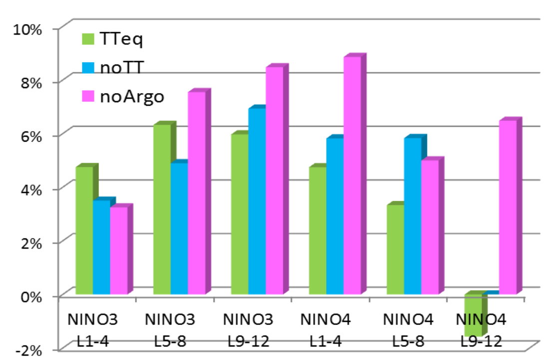

Figure 3.4 - Increase of the RMSE of the NINO3 and NINO4 SST indices in the hindcasts from TTeq, noTT, and noArgo from the RMSE in the hindcasts from ALL normalized by the RMSE in the hindcasts from ALL for L1-4m L5-8, and L9-12. Forecast biases are estimated for each lead month and for each OSE separately, and removed from the forecasted values.

The impact on NINO3 increases for lead time month from 5 to 8 (L5-8) and from 9 to 12 (L9-12). In contrast, the impact on NINO4 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 NINO4 for L9-12. It should be noted that the RMSEs in TTeq are larger than noTT for NINO3 for L1-4 and L5-8, which may indicate the importance of assimilating equatorial and extraequatorial (outside of 2.5˚S-2.5˚N) buoys simultaneously, especially for relatively short lead time forecasts of the NINO3 index. Impacts of Argo are larger than those of TAO/TRITON on both NINO3 and NINO4 for all lead times except for NINO3 indices for L1-4 and NINO4 for L5-8. The impact of Argo on NINO3 is enhanced with increasing lead time, but for NINO4 the impact is not monotonic being smaller for L5-8 than for shorter and longer lead times.

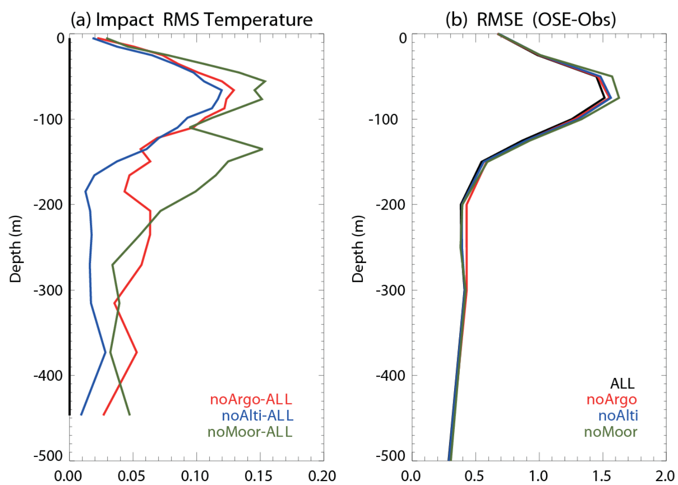

Figure 3.5 - Profiles of the (a) RMSD for temperature in the equatorial Pacific between OSEs and (b) the RMSE for temperature in the eastern equatorial Pacific (90-130˚W, 5˚S-5˚N), computed by comparing the temperature in each OSE with all in situ observations.

3.1.3 Observing system experiments at ECMWF

A series of OSEs has been performed using ECMWF's ocean reanalysis 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 3.5 presents the profile of the RMSD between each OSE and ALL and the profile of the RMSD between all OSEs and the in situ observations.

The former represents the data impact on the analysis; the latter represent the data impact on the error. We find that in the eastern tropical Pacific, whenever any data type is withheld, the fit to in situ temperature profiles degrades. This indicates that all data types contribute some unique information to the data assimilating system. It should, however, be noted that all OSE runs adopt a bias correction scheme, which applies correction to temperature, salinity, and in the equatorial wave-guide, corrections to the pressure gradient. The mean seasonal cycle of the bias correction is estimated a-priori from a previous data assimilation experiment, and therefore implicitly includes information from all observing systems. 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.

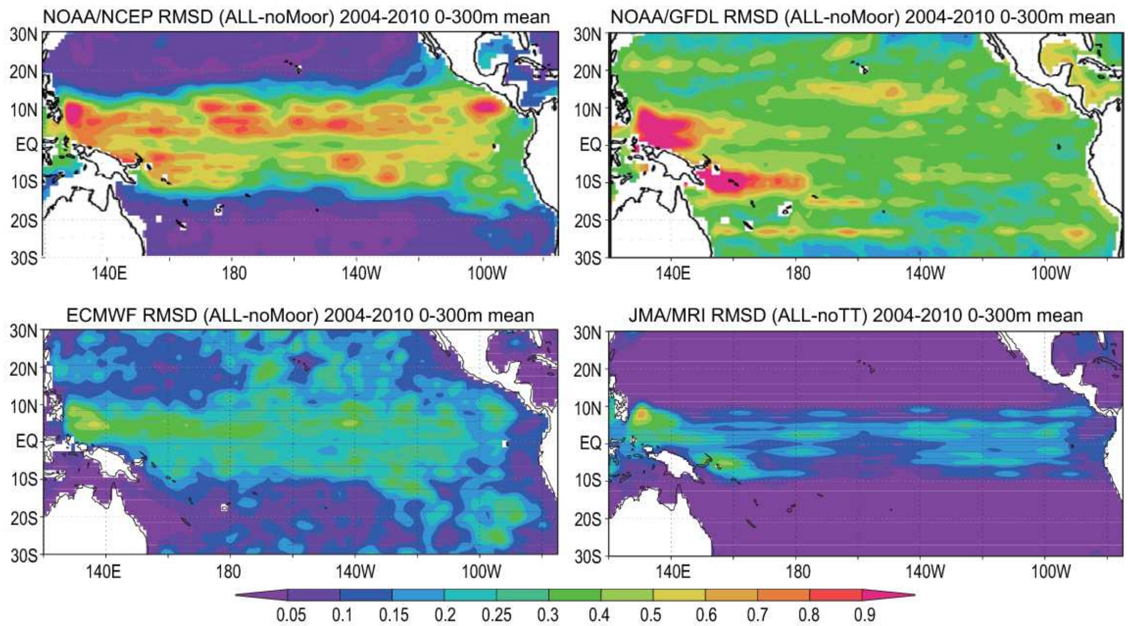

Figure 3.6 - 0-300 m averaged RMSD of temperature (˚C) between ALL and noMoor/noTT in 2004-2011 (2004-2010) for NCEP and GFDL (ECMWF and JMA/MRI).

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 then 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 are i) too limited sample in a forecasting system with large ensemble spread; ii) the impact of the observing system in the mean state through the bias correction is not accounted for.

3.1.4 Observing system experiments at ECMWF

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 centers. For this purpose, an evaluation of OSE results in NOAA (NCEP and GFDL), JMA/MRI, and ECMWF has been initiated using common metrics. Figure 3.6 shows an example of the intercomparison. The averaged RMSD of temperature between ALL and noMoor/noTT in 0-300 m is relatively large in the far western equatorial Pacific, and around 8˚S-160˚E. These are probably regions where the model accuracy is relatively low. The 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. Through this initiative we aim to estimate some general impacts of the observing system which 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. 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 plan to set up Near-Real Time (NRT) OSEs. NRT OSEs 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 2011 with the UK Met Office's operational ocean forecasting system (Lea et al., 2013).

Following this GODAE Ocean View initiative, NRT OSEs were conducted over successive months of the 2013 year by Mercator Ocean. The operational 1/4° global ocean system (Lellouche et al., 2013) is setup for those experiments. During March 2013, TAO/TRITON/RAMA temperature and salinity observations are withheld from the analysis. However, in 2013, some of the TAO mooring observations are not available. The operational ocean analysis and forecasting system used for those experiments is based on a 1/4° global ocean model configuration. The assimilated observations are satellite SSH data, the AVHRR SST maps and the in situ temperature and salinity profiles. No current data are assimilated. A 3D-Var T/S bias correction computed with in situ model-observation misfits available 3 months prior to the analysis is applied below the thermocline. The effect of withholding a part of the in situ data set will then be underestimated for simulations shorter than 3 months due to the memory of this bias correction.

Different observation based statistics and ocean state quantities are compared between the 2 simulations to evaluate the impact of assimilating data from the tropical moorings. Model observation error statistics are computed over the month for both experiments. TAO/TRITON and RAMA observation misfits are included. Figure 3.7 (left) shows that significant differences are found for the mean and RMS temperature misfits in the NINO3 region at the thermocline depth. The higher level of error, RMS or mean, is clearly at the thermocline depth, which is shallower when going eastward. The assimilation of the TAO observation reduces the RMS and means of temperature errors. Under the thermocline, the bias correction is still active and takes into account innovations from the previous 2 months.

Figure 3.7 (right) shows the temperature differences at 100 m depth on the last day of the 1-month experiments. Important differences are visible at and around the moorings and can reach 2°C. Salinity differences are found within the thermocline and 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 probably prevent larger differences in temperature close to the surface; 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).

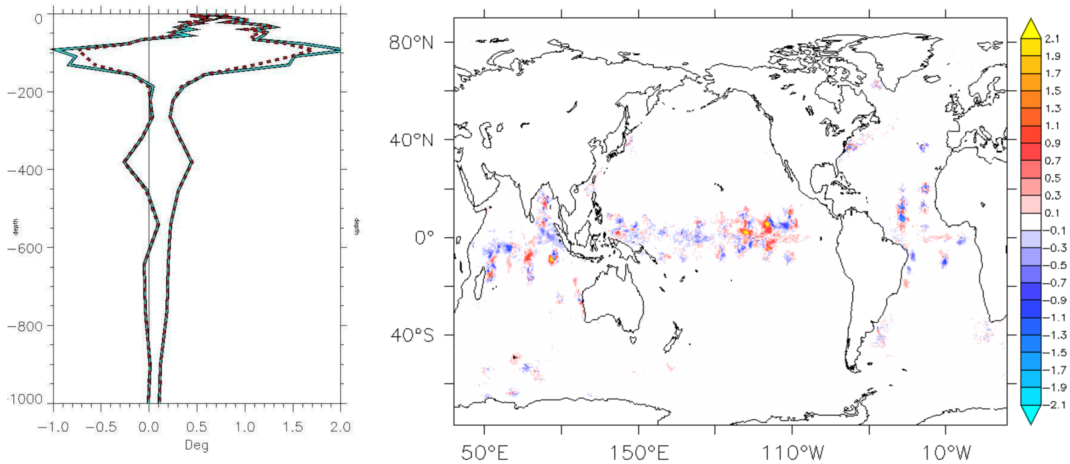

Figure 3.7 – (left) Mean and RMS observation-analysis error to in situ temperature observations in the Nino 3 region with the TAO assimilated in red, without in blue; (right) Temperature differences on the last day of the 1-month experiments with and without TAO observations assimilated at 100 m depth.

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 2011, 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) 3DVAR (Cummings and Smedstad, 2013) on the forecast performance of global Hybrid Coordinate Ocean Model (HYCOM; equatorial resolution of ~1/12º) is achieved by the adjoint-based observation sensitivity technique (Langland and Baker 2004). The technique computes the variation in a measure of the forecast error due to the assimilated data through the adjoint model. Results presented here are from the Pacific domain of global HYCOM cycling with NCODA 3DVAR for the 16 September to 30 November 2012 time period.

Figure 3.8 shows the geographic variation of the impacts of assimilating temperature and salinity profile observation data types on reducing HYCOM 48-hour forecast error. Note that profile levels are treated as independent observations in the assimilation. Figure 3.8 indicates that the majority of temperature profile observations assimilated show beneficial impacts, although non-beneficial impacts are seen in some Argo. Assimilation of salinity observations, however, is always beneficial. Figure 3.8 presents the summed observation impacts for the different profile observing systems.

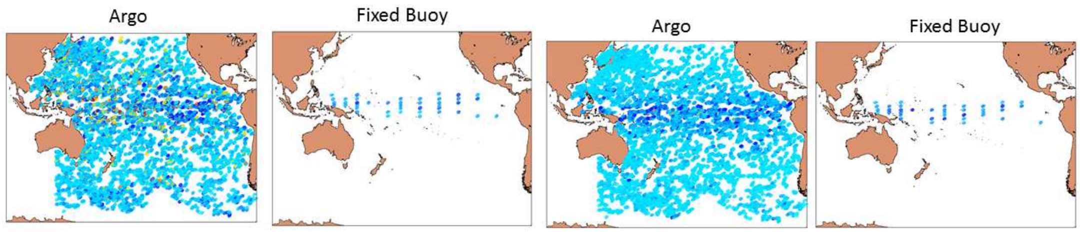

Figure 3.8 - Observation impact of temperature (left 2 panels) and salinity (right 2 panels) observations assimilated in global HYCOM on 48 hours forecasts. Magnitude of the forecast error reduction (increase) from assimilation of the observation is shown as a negative (positive) value. Each point represents the combined impacts of all depth level observations in the vertical profile. Units are °C and PSU.

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 impacts of temperature and salinity from all observing systems are beneficial, with the most beneficial observing system assimilated being the tropical fixed moorings. Figure 3.9 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.

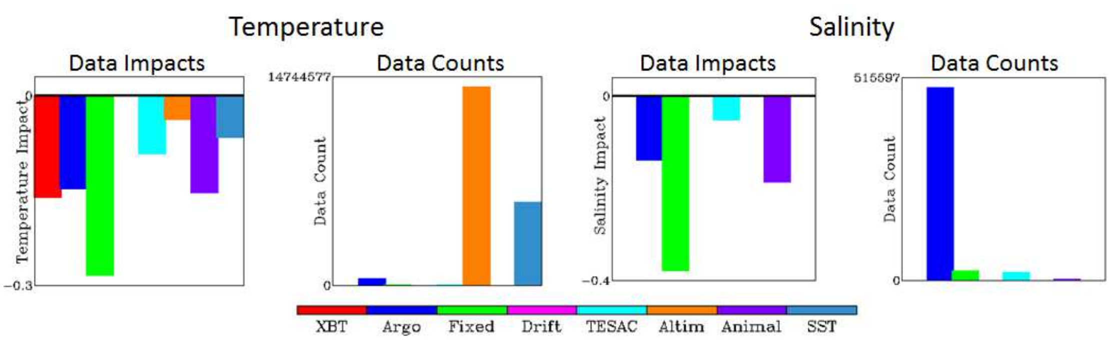

Figure 3.9 - Temperature (°C) and salinity (PSU) observation impacts on 48 hours forecasts normalized by the number of observations and partitioned by observing system. Includes all observations assimilated, i.e., XBT, Argo, Fixed Buoy (Fixed), Drifter (Drift), TESAC, synthetic temperature profiles derived from satellite SSH, Animal sensor, and satellite SST retrievals. Negative data impact values indicate beneficial observing systems.

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 continued routine observing is needed there to adequately constrain the model. It is shown that on a per observation basis the impact of Argo and tropical moorings are equivalent at low latitudes. Argo has the advantage over the moorings of providing improved vertical sampling. An advantage for the moorings is much higher frequency observing than Argo. Daily profiles are available from the moorings, which matches the 24 hour HYCOM assimilation update cycle interval. The two observing systems are thus complementary.

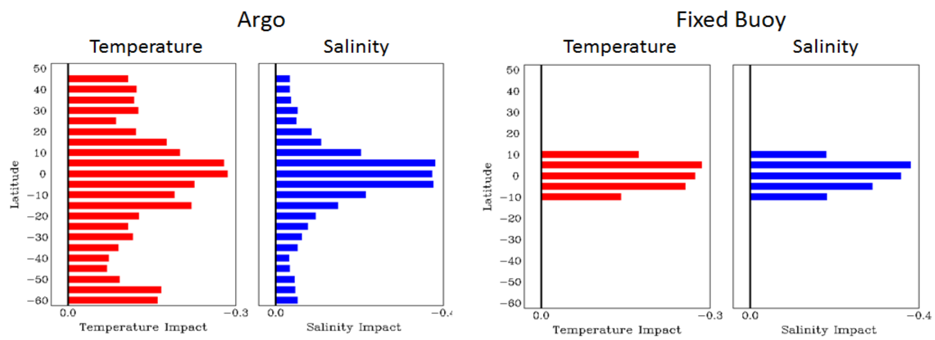

Figure 3.10 - Per observation data impacts on 48 hours forecasts of Argo and fixed buoy arrays for temperature (°C) and salinity (PSU) and partitioned by 5° latitude bands.

3.3 Evaluation for climate research

3.3.1 Evaluation for ocean state estimation

Beside the fact that most of SIDA and OFDA are applicable to some ocean state estimation for climate research, we here focus on the 4DVAR systems that 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 time within the assumed assimilation time-window.

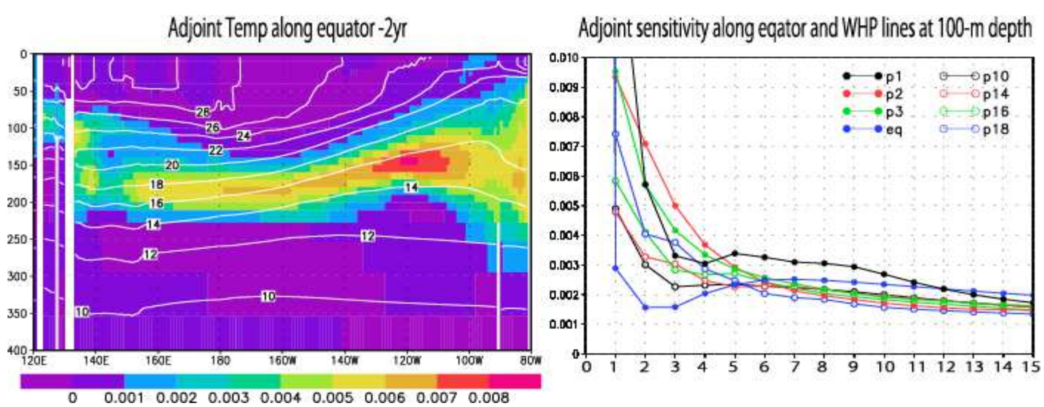

Figure 3.11 – (left) Sensitivity of changes (units in K) in water temperature at the WHP lines at 100-m depth in the Pacific Ocean in the vertical section along 0.5°N at –2 years. Temperature (˚C; white color contours) of the background ocean state is superimposed; (right) Temporal evolution of the sensitivity 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.

A data synthesis system applying the smoothing scheme, in particular, 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 observing system evaluation (e.g., Köhl and Stammer, 2004).

A 4DVAR ocean-state estimation system with 1°×1° resolution, developed as a part of the JAMSTEC–Kyoto University collaborative program (the K7 consortium, Masuda et al., 2013), is used to evaluate an ocean observing system for improved long-term ocean-state estimation (Masuda et al., 2014). 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 World Ocean Circulation Experiment Hydrographic Program (WHP) lines in the Pacific Basin to the retrospective ocean state estimation. 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 zero) when temperature changes at an arbitrary grid point at an arbitrary time in the past.

Figure 3.11 (left) 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 3.11 (right) shows the sensitivity values averaged within each hydrographic line at 100 m. These values show the impact of assumed observations at year zero 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 rates show that equatorial ocean is a key region to be intensively monitored since the local memory of the ocean properties is shorter than that in other regions. This kind of analysis enables us to provide unique information on the effectiveness of an ocean observing system on the retrospective ocean-state estimation although the detailed values of estimated sensitivity depend on the model platform.

In the real ocean, meso-scale 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 meso-scale eddies using the ECCO adjoint (4DVAR) assimilation system (resolution 1/3 to 1/6˚).

3.3.2 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, namely XBT-C, NoOcObs (with and without initialization using ocean observation data), and Assim (Same as XBT-C but the correction of XBT bias is not applied).

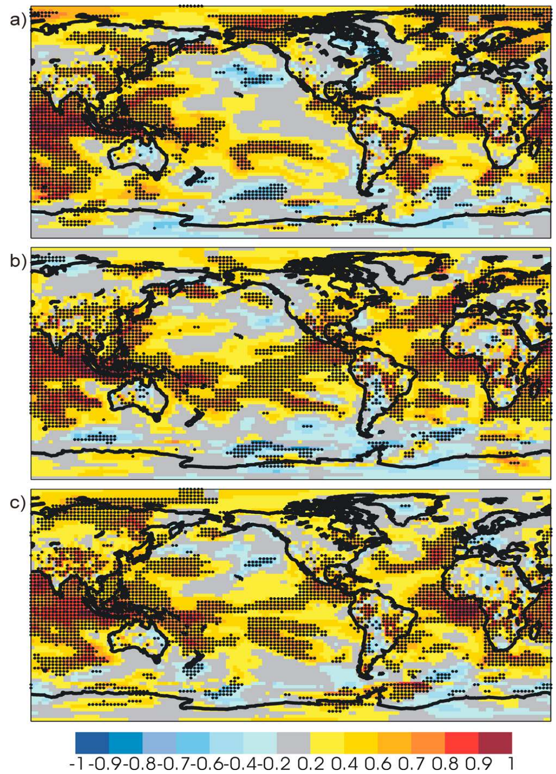

Figure 3.12 - Ensemble mean correlation for near-surface air temperature with respect to the GHCN/ERSST/GISS data set for winter (December to February) over the forecasts period 2 to 5 years of the (a) NoOcObs, (b) XBT-C, (c) Assim experiments. Three member ensemble reforecasts for the period 1960-2005 have been used. The black dots depict the grid points where the correlation is significantly different from zero with 95% confidence (adjusted from Doblas-Reyes et al., 2011).

Figure 3.12 shows improvement of prediction skill for 2 to 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, Polhmann 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 white paper reviewed the current status and achievements of ocean DA systems and discussed their requirements for the tropical Pacific observing system including the TAO/TRITON array and Argo floats. It also summarizes past and current studies to evaluate impacts of those observation data.

Temperature data from TAO/TRITON array are assimilated in most ocean DA systems, and essential for constraining the ocean heat content, stratification and circulation in the tropics. 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 reveals that the recent decrease of TAO/TRITON data severely affects the accuracies of the analyzed fields making it more difficult to issue reliable forecast statements. TAO/TRITON data are also essential for validating ocean DA products.

Observing system evaluation studies always have their limitations. For example, impacts of observing system evaluated through OSEs depend strongly on the quality and characteristics of both the ocean DA systems and the forecasting models used. In particular, current coupled models still have large errors and biases, and there is, thus, a high possibility that observation impacts are severely diminished due to them. It should be also noted that OSE and other observing system evaluation studies can evaluate only the impacts of data that are assimilated in the DA system. Some of the surface meteorology and current meter data from TAO/TRITON moorings are not assimilated, but withheld for evaluation and validation. Some systems do not assimilate salinity data. As such, evaluation through OSEs in which temperature (and salinity) data are withheld will under-estimate the impact of the TAO/TRITON array.

Table 4.1 – Requirements of SIDA systems for TPOS in 2020.

Variable	Accuracy	Vertical	Horizontal	Temporal
SST	0.05K	-	Global/ 0.25˚	more than 20 years/ daily
Ocean Temperature	0.05K	0-250m/ 10m 250-1000m/ 50m	Tropics/ 2˚×10 as the baseline	more than 20 years/ 1-5-daily
SSS	0.1PSU	-	Global/ 2˚	more than 20 years/ 10-daily
Salinity	0.02PSU	0-250m/ 10m 250-1000m/ 50m	Tropics/ 2˚×10˚ as the baseline	more than 20 years/ 1-5-daily
SSH	3cm	-	Global/ 1˚	more than 20 years/ 10-daily
Currents	2cm/s	0-250m/ 20m 250-1000m/ 100m	Tropics/ 5˚×20˚	more than 20 years/ 10-daily

In spite of the limitations above, positive impacts of TAO/TRITON are evaluated in most studies introduced in this paper. Although the evaluated impacts depend on the studies, the impacts are generally around the same level with, and sometimes larger than those of Argo in the equatorial Pacific. Several studies also indicate that profiles from Argo floats cannot compensate the loss of TAO/TRITON data. We, thus, assume that a further loss of data will lead to a degradation of the forecast skill in the tropical Pacific and will have a detrimental impact on many applications based on ocean DA systems.

Table 4.2 – Requirements of OFDA systems for TPOS in 2020.

Variable	Accuracy	Vertical	Horizontal	Temporal
SST	0.05K	-	Global/ 0.1˚	more than 5 years/ daily
Ocean Temperature	0.05K	0-250m/ 10m 250-1000m/ 50m	Global/ 2˚	more than 5 years/ daily
SSS	0.1PSU	-	Global/ 1˚	more than 5 years/ daily
Salinity	0.02PSU	0-250m/ 10m 250-1000m/ 50m	Global/ 2˚	more than 5 years/ daily
SSH	3cm	-	Global/ 0.1˚	more than 5 years/ daily
Currents	2cm/s	0-250m/ 20m 250-1000m/ 100m	several important points (including western boundary currents)	more than 5 years/ daily

We are assured that 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 basic requirements of ocean DA systems for TPOS in 2020 are summarized in Tables 4.1-4.3. 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.

Table 4.3 – Requirements of DA systems for ocean state estimations and decadal predictions for TPOS in 2020.

Variable	Accuracy	Vertical	Horizontal	Temporal
SST	0.05K	-	Global/ 1˚	more than 20 years/ 10-daily
Ocean Temperature	0.002K	0-250m/ 10m 250-1000m/ 50m 1000-bottom/ 250m	Global/ 2˚	more than 20 years/ 10-daily
SSS	0.1PSU	-	Global/ 2˚	more than 20 years/ 10-daily
Salinity	0.002PSU	0-250m/ 10m 250-1000m/ 50m 1000-bottom/ 250m	Global/ 1˚	more than 20 years/ 10-daily
SSH	3cm	-	Global/ 1˚	more than 20 years/ 10-daily
Currents	2cm/s	0-250m/ 20m 250-1000m/ 100m 1000-bottom/500m	several important points (including western boundary currents)	more than 20 years/ 10-daily

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