Climate Prediction Center Analyses and Monitoring in Support of the Ocean Observing System for Climate

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1. Project Summary

Ocean plays a crucial role in controlling global climate variability, and thereby, influences various facets of society. The ocean's control on the atmosphere extends from weather to climate on seasonal, decadal and centennial time-scales, and to diverse phenomenon such as weather and climate extremes, droughts, floods. As a consequence, oceans play an important role in influencing societal well-being, e.g., food security, marine transportation, prediction of droughts and floods etc. Due to their large thermal inertia, and coverage of ~70% of the surface of the globe, ocean monitoring is also a key to understanding and anticipating the potential influence of human induced change in the Earth System, and is the place where such influences would be first detected with confidence.

Given the importance of ocean climate variability, the fundamental outcome of this project - *disseminating a synthesis of the state of the global oceans* - is to deliver ocean information and data sets to the user community to (a) provide a basis to make informed decisions either to mitigate or to take advantage of the influences resulting from the evolving ocean climate conditions (e.g., El Niño-Southern Oscillation), (b) provide enabling datasets to the science community to improve our understanding of ocean climate variability and its causes, and (c) keep a pulse of slowly evolving changes in the ocean. The importance of this project is underpinned by the fact that raw ocean observations do not provide a synthesis view of the state of the ocean, and it is the process of converting individual observations into a form that could be easily understood is required for an end-to-end ocean climate information system.

This project is an ongoing partnership between the Office of Climate Observations (OCO) of the Climate Program Office (CPO) and the Climate Prediction Center (CPC) with a focus on the development, maintenance, and dissemination of *real-time ocean monitoring information and*

products to the user community. The real-time ocean products disseminated as part of this project rely critically on the ocean climate observing system supported and maintained by the OCO, and provide a *synthesis of the state of the global oceans, together with real-time monitoring of ocean climate variability on different time-scales*. The outcomes of the project are crucial for an end-to-end ocean climate delivery information system that connects gathering of the ocean observations (supported by the OCO) to the dissemination of readily usable ocean products to global user community in real-time. Project outcomes also facilitate NOAA's goal to accomplish its societal challenge (a) to mitigate and adapt to vulnerability to weather and climate extremes that are influenced by oceanic variability, and (b) advance understanding and prediction of droughts, floods, and water resources.

2. Scientific and Observing System Accomplishments

2.1. Sub-Task 1: Development and maintenance of a web-site to deliver ocean monitoring and forecast products

The Global Ocean Data Assimilation System (GODAS) website, hosted by the CPC, serves the global user community with real-time ocean monitoring and ocean prediction products. The web-site also provides access to the GODAS data sets that can be used for (a) improved understanding of ocean climate variability, and (b) validating different *in situ* ocean observing systems. Starting from 1979 onwards, the web site contains plots of climatology and anomalous fields of various oceanic variables over different basins of the global ocean, and covers time scales from weekly to interannual to decadal.

Under this sub-task, specific work items and products delivered in FY14 were:

Maintain the GODAS website and respond to user's requests: We continued to maintain the ocean monitoring website to disseminate the real-time ocean climate information to the user community. Components of ongoing activities included: routine maintenance of the ocean product delivery web-site; monitoring website statistics; providing responses to the user queries in a timely manner.

Deliverable: Real-time ocean climate information, for example, SST, ocean heat content, air-sea exchanges of heat, momentum and fresh water, sea level, to the global user community.

Maintain "Monthly Ocean Briefing: To synthesize available ocean information, we hosted the "Monthly Ocean Briefing" (MOB), which is an expert assessment of the recent evolutions of the state of ocean and associated atmospheric conditions, and ocean forecasts delivered via a conference call around the 7th day of each month. We solicited feedbacks on the ocean briefing, and included additional analysis as needed to address unique climate events. In addition, we monitored the data return status of the TAO mooring arrays and explored the relationship between spatial and temporal density of TAO observations and uncertainties of tropical Pacific temperature anomalies by comparing six operational ocean reanalyses (see section on "real time

ocean reanalyses intercomparison") and discussed influence of uncertainties in ocean analysis on ENSO prediction.

To improve our understanding and prediction of ENSO, we developed *new ENSO monitoring tools* incorporating recent advances in our understanding of ENSO. We noted that the warm water volume (WWV) index, a measure of warm water pool above the depth of 20 degree isotherm (D20), is no longer a good precursor for ENSO development after 2000. We then examined the relationship between D20 variations and El Niño and La Niña events separately for the period before and after 1999. The analysis suggested that D20 variations in the central tropical Pacific (CTP index) was a good precursor for ENSO events for the two periods, while the WWV index was a good precursor only before 1999 (Fig. 1, Wen et al. 2014). We also found the decadal changes in the relationship between D20 and ENSO to be associated with a strengthening of subtropical cell circulation around 1999. The CTP index is now monitored in real-time in support of ENSO monitoring and prediction.

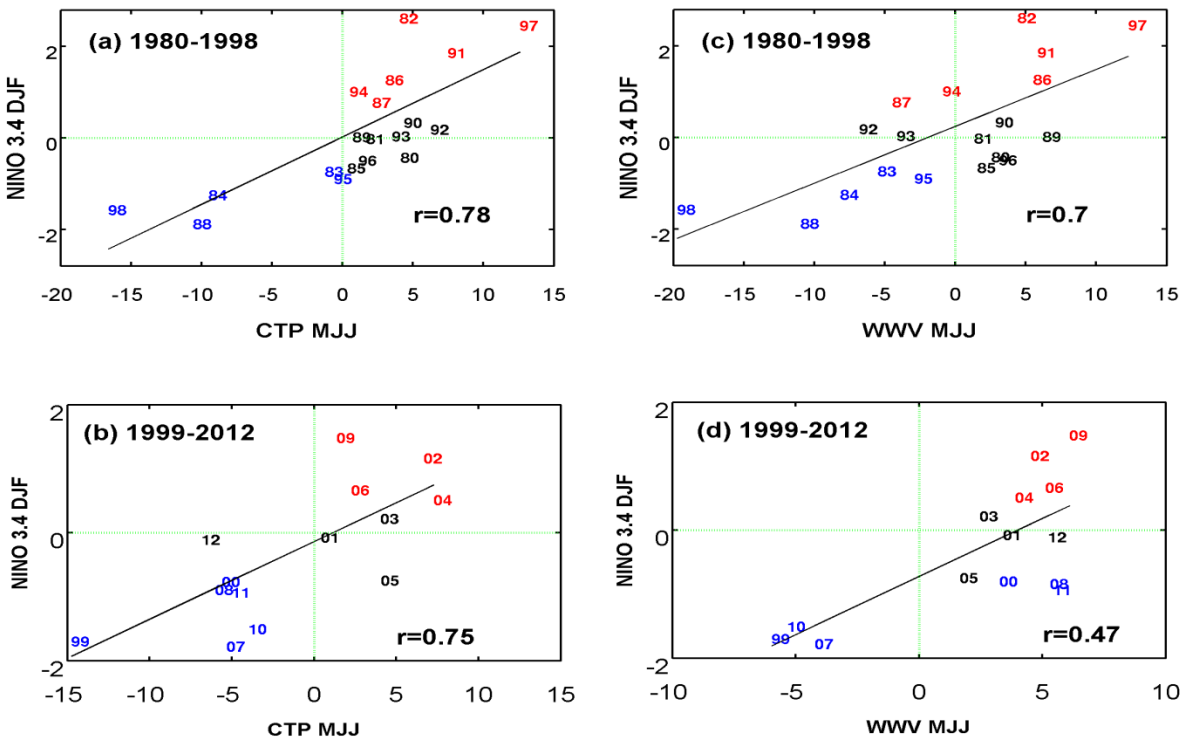

Fig. 1. Scatter plots of the cental tropical Pacific (CTP) and Niño 3.4 indices for the period (a) 1980-1998 and (b) 1999-2012. CTP is the average for May-June-July (MJJ). Niño 3.4 is the average for December-January-February (DJF) and the numeral denote the last two digits of the year (e.g. DJF '10' means from December 2010 to February 2011). The red, blue and black colors represent El Niño, La Niña and ENSO neutral years, respectively; r denotes the correlation coefficient. (c) and (d) are the same as (a) and (b) except for the WWV.

Deliverable: An expert assessment of the recent evolutions of the state of global oceans and ocean forecasts on a monthly basis.

Maintain "Annual Ocean Review" and lead the SST section in the BAMS Annual Climate Report: In early February 2014, we provided the "Annual Ocean Review" (AOR) summarizing the major features of the state of global oceans in 2013, and we also led SST section in the Ocean Chapter. The AOR included a set of GODAS-based analysis to mimic the plots in other sections in the Ocean Chapter of the BAMS Annual Climate Report.

Deliverable: Annual contribution to the "Ocean Chapter" of the BAMS Annual Climate Review.

Participated in ocean reanalyses intercomparison project (ORA-IP): The CLIVAR Global Synthesis and Observations Panel (GSOP), together with GODAE OceanView (GOV), jointly initiated the ocean reanalyses intercomparison project (ORA-IP). The objective of this project is to assess uncertainties among ocean reanalyses in estimation of many physical fields such as ocean heat content, sea surface steric height, mixed layer depth and surface fluxes. We contributed both the GODAS and Climate Forecast System Reanalysis (CFSR) data sets to the intercomparison. The results of the project will be published in the Climate Dynamics Special Issue on Ocean (and Sea Ice) Reanalyses in 2015.

Deliverable: Compare GODAS and CFSR with other ocean reanalyses and identify deficiencies in GODAS and CFSR.

Initiated real-time ocean reanalyses intercomparison project (RTORA-IP): The ORA-IP includes ocean reanalyses from both research community and operational centers, and is an opportunity to extend ORA-IP to near real-time. In addition, in the era of declining TAO/TRITON array, and an evolving ocean observing system, there is a need to assess the influences of changes in the ocean data on the tropical Pacific analyses in real time. Recognizing this need, we initiated a real time ORA-IP (RTORA-IP). We collected ocean reanalysis products from six centers (NCEP, ECMWF, JMA, GFDL, NASA, BOM), and developed a suite of ensemble products that includes the ensemble mean and ensemble spread for the upper 300m ocean temperature, upper 300 ocean heat content (HC300) and depth of 20 degree isotherm anomalies in each ocean basin and global ocean (http://www.cpc.ncep.noaa.gov/products/GODAS/multiora_body.html).

The ensemble means are used to monitor the best estimate of ocean climate variability and the ensemble spreads to monitor uncertainties among ocean reanalyses. We found that the ensemble spreads among ocean reanalyses are sensitive to in situ data distributions. Fig. 2 shows that the spread of temperature anomalies in the eastern tropical Pacific (160°W-110°W, 5°S-5°N) usually increased when the number of TAO temperature profiles in that region decreased. It is also noticed that the ensemble spread decreased significantly in October 2014 when the two TAO mooring lines at 140°W and 125°W were restored. Interestingly, the ensemble spread west of 140°E continued to be large where there were little observations (http://www.cpc.ncep.noaa.gov/products/GODAS/insitu/anum_xt_short.gif).

The preliminary results of the project have been reported at the Pan-CLIVAR meeting in Hague, Netherlands in July 2014. Since then, two new ocean reanalyses from UK Met Office and MERCATOR expressed willingness to join the project. To accommodate the two new ocean reanalyses, which covers from 1993 onward, we will recalculate anomalies based on the 1993-2013 climatology, and maintain two separate web sites, one for the 1981-2010 climatology with 6 reanalyses products and another for the 1993-2013 climatology with 8 reanalyses products. We will discuss the plan with the community at the 2nd GOV Observing System Evaluation Task Team (OSEval-TT) and GSOP Workshop to be held in Toulouse, France, in December 2014.

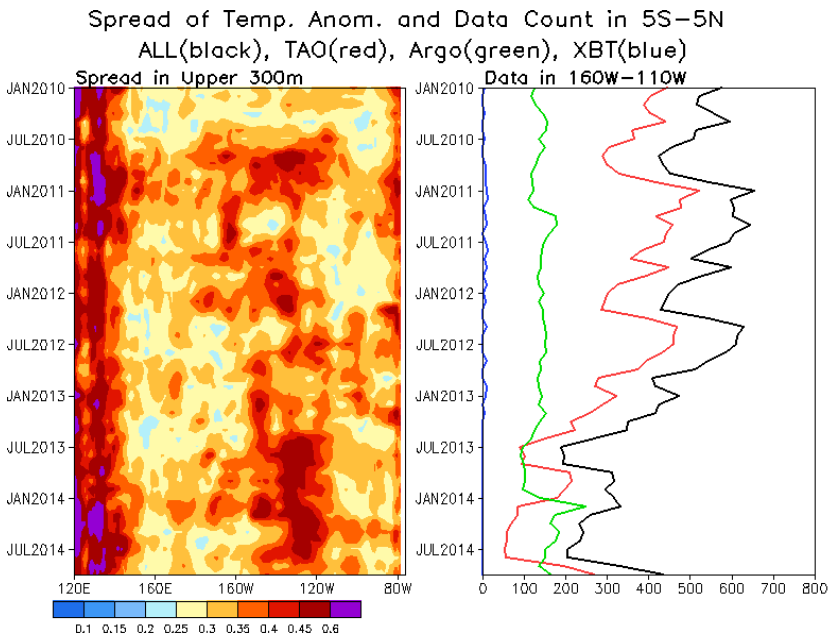

Fig. 2. Longitude-time plot of ensemble spread of temperature anomalies among six ocean reanalyses averaged in 5°S-5°N and upper 300m (left column). Number of daily temperature profiles accumulated in 160°W-110°W and 5°S-5°N from TAO (red line), Argo (green line), XBT (blue line) and total (black line).

Deliverable: Monitor ocean climate variability using ensemble of ocean reanalyses and explore linkages between uncertainties among ocean reanalyses and gaps in ocean observing systems

2.2. Sub-Task 2: Development of an Ocean Observing System Evaluation (OSE) capability and assessment of the utility of the TAO array

We led a NOAA effort in coordinating an OSE capability based on multi-analysis approach. The requirement for this activity stems from (a) resource limitations on the maintenance of TAO moored array in the equatorial tropical Pacific, and (b) possibility of alternate ocean observing systems that may complement TAO observations. Further, informed decisions about the observing system need to have a sound scientific basis to ensure that NOAA's monitoring and prediction requirements in the tropical Pacific are maintained. Towards this, a multi-analysis approach OSE capability to gain confidence in an OSE based is essential.

We conducted coordinated OSEs and hindcast experiments using the NCEP and GFDL ocean data assimilation systems and seasonal forecast models for the post-Argo period 2004-2011.

Four OSE runs were made with the NCEP Global Ocean Data Assimilation System (GODAS) and GFDL Ensemble Coupled Data Assimilation (ECDA), in which no observations (CTL), all observations (XBT, moorings, Argo) (ALL), all except the moorings (noMoor), and all except the Argo (noArgo) data were assimilated. We evaluated the mean biases, standard deviation (STD) biases, root-mean-square error (RMSE) and anomaly correlation coefficient (ACC) against observations and analyzed fields.

The influences of ocean observations on simulation of HC300 anomalies are shown in Fig. 3. Without assimilation of in situ observations (CTL), ECDA had larger RMSE than GODAS, which was about 60-80% of STD in the eastern tropical Pacific and northwestern tropical Pacific (Fig. 3h). However, both GODAS and ECDA had large RMSE north of 5°N that was 80-100% of STD. The RMSD was significantly reduced by assimilation of all in situ profiles (Fig. 3a, b). When mooring data was removed, the RMSE increased in the eastern Pacific in GODAS (Fig. 3c), and in the western Pacific in ECDA (Fig. 3d). On the other hand, removing Argo data dramatically increased RMSE in GODAS poleward of 5°. In comparison, for ECDA, removing Argo data only increased RMSE outside of the TAO/TRITON array as expected (Fig. 3f). This result suggests that the ECDA is less sensitive to the Argo data than the GODAS.

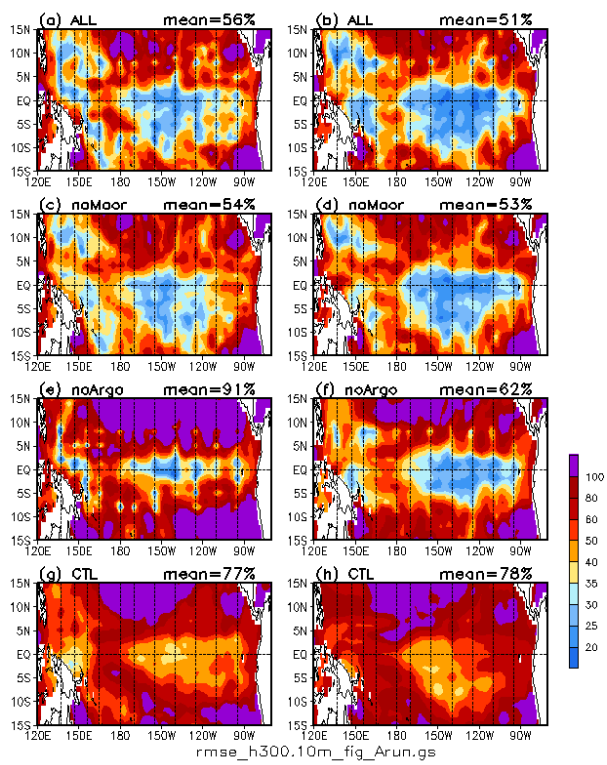

Fig 3. Root-mean-square error (RMSE) of upper 300m ocean heat content (HC300) anomaly with EN4 in 2004-2011 normalized by standard deviation (STD) of HC300 anomaly from EN4 for GODAS (left column) and ECDA (right column) experiments. Unit is %. The average normalized RMSE in the domain is shown on the top of each panel. The vertical dashed lines indicate where the TAO/TRITON buoys are located.

In summary, assimilation of all in situ data (ALL) significantly reduced biases and RMSE in all variables except the zonal current near the equator. For temperature analysis, the mooring data was more critical than the Argo data in the equatorial Pacific, but the Argo data was more important than the mooring data in off-equatorial regions. For salinity analysis, the Argo data was essential in constraining large RMSE in model salinity in both systems. Related to the

improvement in salinity analysis, the Argo data also significantly improved sea surface height (SSH) analysis and surface current analysis in both systems. The impacts of mooring data on SSH and surface current were relatively weak and confined to the central-eastern Pacific in GODAS and in the far western Pacific in ECDA.

The results have been summarized in a journal paper entitled "Evaluation of Tropical Pacific Observing Systems Using NCEP and GFDL Ocean Data Assimilation Systems". The paper has been submitted to Climate Dynamics.

Deliverable: Development of a NOAA capability for Ocean Data Assimilation Experiments for assessing the utility of various oceanic observing systems, particularly in the Tropical Pacific.

2.3. Sub-Task 3: Global oceanic precipitation and SSS analyses in support of understanding air-sea exchange of fresh water and its influence on surface salinity

In FY14, we continued our efforts to update and improve our sea surface salinity (SSS) and precipitation analyses. We developed a package of analyses for global sea surface salinity and associated fresh water flux, including the NOAA Blended Analysis of Sea-surface Salinity (BASS), CMORPH precipitation, CFSR evaporation. We established and refined a set of routine procedures to produce the package on a real-time basis and provide it to CPC Monthly Ocean Briefing and CPC Monthly Climate Review. The outcomes of this effort contribute to OCO's goal to provide better estimate of freshwater fluxes, and budget over the oceans.

Under this sub-task, specific work items and deliverables include:

<u>CMORPH Global Precipitation Analyses</u>: In FY2014, we continued to update and improve our global precipitation analyses. In FY13, we have completed the CMORPH reprocessing for 1998 to present, performed magnitude adjustment against a long-term record (pentad GPCP) of low time/space resolution, and validated the CMORPH against in situ precipitation measurements from moored buoys of TAO/TRITON, PIRATA, and RAMA. The results showed excellent performance of CMORPH in the representation the patterns and absolute magnitude of oceanic precipitation at the buoy locations. In FY14, we continued the routine updates of CMORPH precipitation estimates and provided them to the CPC Monthly Ocean Briefing and CPC Monthly Climate Review for the real-time monitoring and attribution of oceanic fresh water flux and the SSS variations.

Deliverable: Updated CMORPH high-resolution global oceanic precipitation estimates and maps of precipitation estimates.

<u>CMAP global precipitation analyses:</u> In FY2014, we optimized the processing procedures to construct CMAP monthly precipitation analyses with improved efficiency. As a result, monthly CMAP global precipitation analyses is now updated once a month within seven days after the end of the target month, in time for real-time monitoring of global ocean and climate at CPC and other operational centers. CMAP monthly precipitation analysis now covers a 36-year period from 1979 to the present. An example of the CMAP monthly precipitation generated on a real-time basis for October 2014 is illustrated in figure 4.

Deliverable: Analysis of oceanic precipitation and estimate of a component of freshwater flux on a finer resolution.

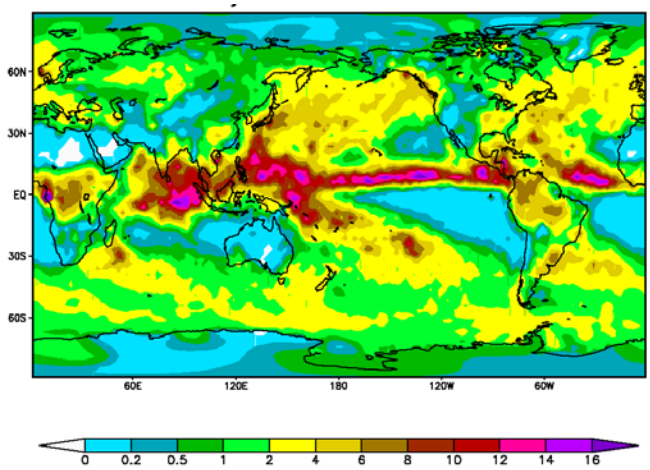

Figure 4: Global Precipitation distribution (mm/day) for October 2014, depicted by CPC Merged Analysis of Precipitation (CMAP).

<u>Construction of a global sea-surface salinity and fresh water budget analyses package:</u> In FY14, we constructed a processing system to produce NOAA blended analysis of sea surface salinity (BASS) on a quasi real-time basis. Furthermore, we developed an analysis package of global sea-surface salinity (SSS) and fresh water flux. This work was built upon our achievements of past years on the salinity and precipitation analyses supported by this project. As a first step of building this salinity – fresh water monitoring tool, the package is composed of monthly fields of NOAA Blended Analysis of Sea-surface Salinity (BASS), CMORPH satellite precipitation estimates, and CFSR evaporation. We explored the possibility of including river runoff as an additional component of fresh water budget monitoring but decided not to pursue this approach further due to limited availability on a real-time basis.

Starting from March 2014, the global SSS and fresh water flux monitoring package is generated on a real-time basis for use by the CPC Monthly Ocean Briefing and CPC Monthly Climate Review. This package is also released to general public through ftp. An example of the SSS – fresh water flux monitoring package for October 2014 is included in the attachments of this report. Anomalies of monthly SSS and fresh water flux anomaly for the same month, a part of the monitoring package, is shown in figure 5.

We also started to refine the package for the real-time production of the SSS/Fresh-Water package at a refined time resolution of pentad mean. Preliminary work showed encouraging results in constructing the pentad SSS analysis capable of depicting SSS variations of intra-seasonal time scales.

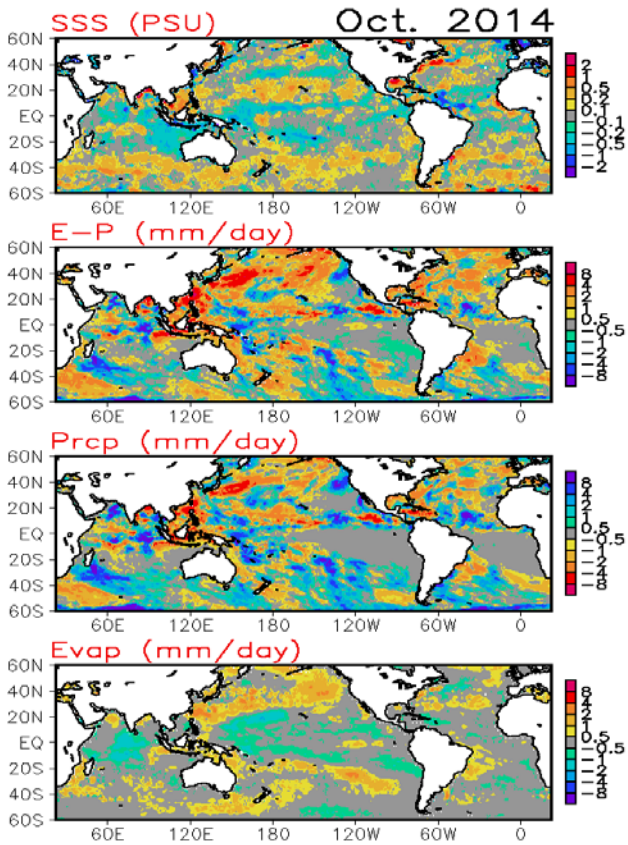

Figure 5: Anomalies of monthly SSS (top, PSU), precipitation (P) (3rd from top, mm/day), evaporation (E) (bottom, mm/da), and E-P (2nd from top) for October 2014. The SSS is based the NOAA blended analysis of surface salinity (BASS, Xie et al. 2014), while the precipitation and evaporation are from the CPC Morphing technique (CMORPH, Joyce et al. 2004) and the NCEP CFSR, respectively.

Deliverable: A package of sea-surface salinity and oceanic fresh water flux for near real-time monitoring

Diagnostic study of SSS - fresh water flux relationship: Development of the SSS analysis is a unique opportunity to provide an independent constraint on the estimate of fresh water flux over the oceans. We continued our study on the relationship between SSS and the fresh water flux taking advantage of the CMORPH high-resolution global precipitation analysis and the SSS data from both the individual sources (Argo, SMOS, and Aquarius) as well as the blended analysis described in previous section.

During FY2014, we started the examination of the co-variability among SSS and E-P using the monthly blended SSS, precipitation and evaporation data. In particular, inspections of the variations in recent months showed that while enhanced precipitation always leads to reduced salinity over open ocean, increases in salinity are often slower involving multiple oceanic and atmospheric processes and their interactions. In addition, salinity over coastal regions is largely influenced by runoffs from large rivers especially during local raining seasons. Further work is underway to quantify the processes using data for the recent four years.

Deliverable: Constraining estimates of freshwater flux over the ocean with changes in salinity and vice versa.

3. Outreach and Education

3.1. Ocean products

We served a broad user community for our global ocean monitoring products. Through our "Monthly Ocean Briefing" we continued to maintain a relationship with users. Following are a some examples signifying the impact of deliverables under this project:

The ocean briefing PPT has been routinely reviewed by a broad user community:

> NOAA/NASA/NCAR: Dr. David Legler, Dr. Diane Stanitski, Dr. Frank Schwing, Dr. Mike McPhaden, Dr. Billy Kessler, Dr. Marty Hoeling, Dr. Tim Boyer, Dr. Dick Crout, Dr. Richard Bouchard, Dr. Kevin Trenberth, Dr. Tony Lee, Dr. Guilaume Vernieres, Dr. Tony Rosati, Dr. Gabriel Vecchi, Dr. Andrew Wittenberg, Dr. Chunzai Wang,, Dr. Chris Landsea, Dr. Nathan Mantua,
>
> Private industries: Dr. Klaus Weickmann, , Dr. David Enfield,
>
> Academia: Dr. Mike Peterson, Dr. Mark Cane, Dr. Ragu Murtugudde, Dr. Paul Roundy, Dr. Phil Klotzbach, Dr. Lisan Yu, Dr. Janet Sprintall, Dr. Nick Bond, Dr. Jame Kinter, Dr. Bohua Huang, Dr. Ed Schneider, Dr. Lisa Goddard, Dr. Tony Barnston, Dr. Shanping Xie, Dr. Feifei Jin, Dr. Bin Wang, Dr. Bruce Anderson, Dr. Ben Kirtman, Dr. Matt Newman
>
> International community: Dr. Magdalena Balmaseda from ECMWF, Dr. Yosuke Fujii from JMA, Dr. Harry Hendon and Dr. Oscar Alves from BOM, Dr. Matthew Martin from UK Met Office, Dr. Fabrice Hernandez from MERCATON, Dr. Dake Chen and Dr. Weidong Yu from China, Dr. Ken Takahashi from Peru, Dr. Bill Merrifield from Canada.

The ocean briefing plots have been used as teaching materials for high school, college and graduate students. They are routinely used at CPC in support of ENSO prediction, hurricane prediction and temperature and precipitation outlooks . They are also used by the Intra-Americas Study of Climate Processes (IASCLiP) Forecast Forum (http://www.eol.ucar.edu/projects/iasclip) and many operational centers around the world.

The PDO index used in the ocean briefing had switched from a persistent negative PDO phase to a positive phase in spring 2014, coincident with the onset of positive SST anomalies in the central equatorial Pacific. However, PDO indices from different sources had large differences during the transition period and caused confusions in the user community. To understand uncertainties among PDO indices, we systematically evaluated the methods used in deriving PDO indices from different centers. The results have been summarized in a short paper entitled "Factors contributing to uncertainty in Pacific Decadal Oscillation index". The paper has been recently accepted by Geophysical Research Letters.

The research works supported by this project has been reported in various peer reviewed journals, conferences, and workshops. The well-known works include studies of the mixed layer heat budget and AMOC variations using GODAS; an assessment of the CFSR ocean component, a comparative analysis of ensemble operational ocean reanalyses; studies of prediction skill and predictability of ENSO and PDO.

3.1. Precipitation Products

CPC satellite based precipitation products are widely used around the world in research, development, operation and service activities in meteorology, oceanography, ecology, health, fishery and many other areas. Two papers describing the CMAP precipitation data sets have been cited more than 4000 times by peer reviewed articles. A paper describing the CMORPH high-resolution satellite precipitation data has a citation index of more than 800. Both the CMAP and CMORPH satellite precipitation data sets are available publically through ftp from CPC server.

The NOAA Blended Analysis of Surface salinity (BASS) has been constructed, as part of this project, for a four-year period from January 2010 and is updated on a real-time basis. The BASS data set is also release publically through ftp.

3.2. Relevant websites for dissemination of information

Ocean Products and Monthly Ocean Briefings:
http://www.cpc.ncep.noaa.gov/products/GODAS

Real time multiple ocean reanalyses intercomparison:
http://www.cpc.ncep.noaa.gov/products/GODAS/multiora_body.html

Preciptation data:
ftp://ftp.cpc.ncep.noaa.gov/precip/

NOAA Blended Analysis of Surface Salinity (BASS):
ftp://ftp.cpc/ncep.noaa.gov/precip/BASS

4. Publications and Reports

4.1. Publications by Principal Investigators

- Published

Xie, T., T. Boyer, E. Bayler, Y. Xue, D. Byrne, J. Reagan, R. Locarnini, F. Sun, R. Joyce, and A. Kumar, **2014**: An in situ - satellite blended analysis of global sea surface

salinity. *J. Geophy. Res. (Oceans)*, 119, 6140 - 6160, doi: 10.1002/2014JC010046.

Wen, C., A. Kumar, Y. Xue, and M. McPhaden, **2014**: Changes in Tropical Pacific Thermocline Depth and Their Relationship to ENSO after 1999. *J. Climate*, **27**, 7230-7249.

Xue, Y., Z.-Z. Hu, A. Kumar, V. Banzon, T. Smith, and N. Rayner, **2014**: Global oceans: Sea surface temperature. *In State of the Climate in 2013*. J. Blunden and D.S. Arndt, eds., *Bull. Amer. Meteorol. Soc.*. **95**, S51-S54..

Kumar, A., H. Wang, Y. Xue and W. Wang, **2014**: How much of monthly subsurface temperature variability in equatorial Pacific can be recovered by the specification of sea surface temperatures? *J. Climate*, **27**, 1559-1577.

Kumar, A., and Z.-Z., Hu, **2014**: How variable is the uncertainty in ENSO sea surface temperature prediction? *J. Climate*, **27**, 2779-2788.

Capotondi, A. & Co-authors, **2014**: Understanding ENSO diversity. *Bull. Amer. Meteorol. Soc.*, doi: http://dx.doi.org/10.1175/BAMS-D-13-00117.1

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Wen, C., A. Kumar, and Y. Xue, **2014**: Factors contributing to uncertainty in Pacific Decadal Oscillation index. Geophys. Res. Lett., DOI: 10.1002/2014GL061992

Balmaseda and co-authors, **2014**: The Ocean Reanalyses Intercomparison Project (ORA-IP). *To appear in J. Opera. Oceanogr. (GODAE Ocean View special issue).*

Kumar, A., and H. Wang, **2014**: On the Potential of Extratropical SST Anomalies for Improving Climate Predictions. *Climate Dynamics*, to appear.

Huang, B, and Co-authors, **2014**: Climate Drift of AMOC, North Atlantic Salinity and Arctic Sea Ice in CFSv2 Decadal Predictions. *Climate Dynamics*, to appear.

- Submitted

Xue, Y., C. Wen, X. Yang, D. Behringer, A. Kumar, and G. Vecchi, **2014**: Evaluation of tropical Pacific observing system using NCEP and GFDL ocean data assimilation systems. *Submitted to Climate Dyn.*

Fujii. Y., J. Cummings, Y. Xue, A. Schiller, T. Lee, M.A. Balmaseda, E. Remy, S. Masuda, G. Brassington, O. Alves, B. Cornuelle, M. Martin, P. Oke, G. Smith, and X. Yang, **2014**: Evaluation of tropical Pacific observing system from the ocean data assimilation perspective. *Submitted to Q. J. R. Meteorol. Soc.*

Kumar, A., M. Chen, Y. Xue, and D. Behringer, **2014**: An analysis of the temporal evolution of ENSO skill and equatorial Pacific ocean observing system: Can a relationship be discerned? *Submitted to Mon. Wea. Rev.*.

4.2. Other Relevant Publications