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

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1. Abstract

This project is a partnership between the Climate Observations Division (COD) of the Climate Program Office (CPO) and the Climate Prediction Center (CPC) with a focus on the development and dissemination of *real-time ocean monitoring products* to the user community. The real-time ocean products developed by CPC rely critically on the ocean climate observing system supported and maintained by the COD, 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 COD) to the dissemination of readily usable ocean products to global user community in real-time.

2. Project Summary

Ocean plays a crucial role in controlling the global climate variability influencing various facets of society. The ocean's control on atmospheric variability extends from weather to climate variability on seasonal, decadal and centennial time-scale. Oceans are also an important source of societal well being, e.g., food security, transportation etc. Due to their large thermal inertia, and a spatial coverage that exceeds 70% of the globe, ocean monitoring is also a key to understanding the influence of human induced change in the Earth system, and is the place where such influences would be detected first with confidence.

Given the importance of ocean climate variability the outcome of this project - *disseminating a synthesis of the state of the global oceans* – delivers the information to the user community which is utilized to (a) make informed decisions to either mitigate or to take benefit from the consequences resulting from the ocean climate variability (e.g., ENSO), (b) improve understanding of ocean climate variability and its causes, and (c) keep a pulse of slowly evolving changes in the ocean state. The importance of this project is underpinned by the fact that raw

ocean observations seldom provide a synthesis about the state of the ocean, and it is the process of converting individual observations into a synthesis in a form that could be easily understood, is what is required for an end-to-end ocean climate information system.

The sub-tasks under this project, and their brief summary, include:

(a) *Development and maintenance of a web-site for routine delivery of ocean monitoring and forecast products:* The deliverable of this task is to maintain and improve a comprehensive web based information delivery system for the ocean products that rely on an operational Global Ocean Data Assimilation System (GODAS) at the National Centers for Environmental Prediction (NCEP). The web site, hosted by the Climate Prediction Center (CPC) of the NCEP, serves the global user community with synthesis products related to real-time monitoring and forecast products of the oceans climate variability on different time scales.

(b) *Development of an ocean Observing System Evaluation (OSE) capability and assessment of the utility of the TAO array:* The deliverable of this task is to evaluate the adequacy of the TAO array with various design configuration options in the equatorial tropical Pacific, and assess impact on the forecasts on seasonal and interannual time-scale. A need for such an ongoing assessment is dictated by the convergence of several factors: (a) The maintenance of the TAO array has seen increasing financial commitments on the part of the NOAA because escalation in costs, and (b) recent advances in the observing system, e.g., Argo, may complement the observations based solely on the TAO array.

(c) *Global oceanic precipitation analysis in support of understanding air-sea exchange of fresh water and its influence on surface salinity*: The deliverable of this task is development of improved oceanic precipitation analysis to constrain the global hydrological cycle, and to compare P-E (Precipitation – Evaporation) estimates against the changes in surface salinity

3. Scientific Accomplishments

A summary of the achievements for different sub-tasks under this project is given below.

3.1 Sub-Task 1: Development and maintenance of a web-site for routine delivery of ocean monitoring and forecast products

3.1.1. Maintenance of the GODAS website and "Monthly Ocean Briefing": The GODAS web site (http://www.cpc.ncep.noaa.gov/products/GODAS) provides the user community an easy access to a synthesis of the ocean state. Over the past year, we monitored the products on the web to ensure that all the products are appropriately updated and accurate. We also provided the user community an expert assessment of the recent evolutions and current conditions of the state of the global ocean, its interactions with atmosphere, and an assessment of SST predictions through the "Monthly Ocean Briefing" (MOB). The MOB is composed of a conference call and PowerPoint presentation, and is held around the 7th day of the month.

In FY11 we made several significant changes to the content of the ocean briefing PPT: we adjusted the climatology base period to 1981-2010, which used to be different for different data sets; we revised SST prediction plots to include the predictions from both CFSv1 and CFSv2 models; we included the National Multi-Model Ensemble (NMME) SST forecasts that include seven climate coupled models. Since October 2011, we have also included a set of new plots that address some unique climate features such as the current negative PDO, the 2011 North Atlantic Hurricane Season, and the persistent atmospheric and oceanic conditions. The ocean briefing PPT, is also made available on the web site, and is accessed by a broad user community (see Fig. 1 for number of unique user accessing the ocean briefing each month).

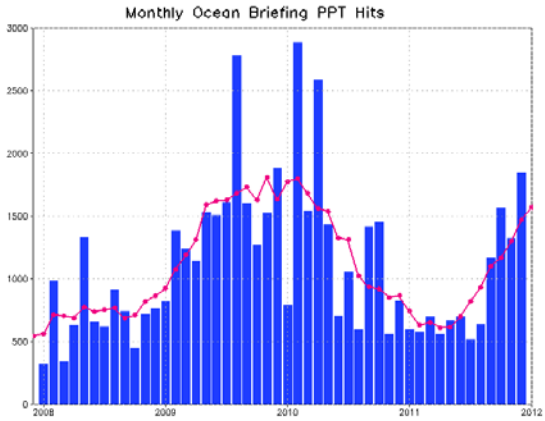

Fig. 1. Monthly statistics of web hits on the "Monthly Ocean Briefing" PPT for January 2008 – November 2011.

Outcome of the task 3.1.1, by providing real-time monitoring of modes of climate variability, addressed the COD program deliverable # 1.

<u>3.1.2 Assessment of the ocean component of the Climate Forecast System Reanalysis (CFSR) and development of CFSR-based ocean monitoring products</u>: At NCEP, a reanalysis of the atmosphere, ocean, sea ice and land over the period 1979–2009, referred to as the climate forecast system reanalysis (CFSR), was recently completed. To assess suitability of CFSR for real-time ocean monitoring, we conducted a comprehensive assessment of the oceanic variability in the CFSR (Xue et al. 2011). Since the CFSR represents a new effort with first guess from a high-resolution coupled system, we also analyze prospects for improved description of small scale air-sea interactions by CFSR, e.g., depiction of Tropical Instability Waves (TIWs) in the eastern equatorial Pacific (Wen et al. 2012).

Outcome of the task 3.1.2, by providing real-time monitoring of modes of climate variability, addressed the COD program deliverable #1.

<u>3.1.3 Comparative analysis of upper ocean heat content from an ensemble of operational ocean analyses:</u> Upper ocean heat content (HC) is one of the key indicators of climate variability on different time-scales. *Since monitoring of the HC is also one of the performance measures for the COD, quantifying uncertainty in its estimate is of particular interest.* The availability of multiple operational ocean analyses (ORA) that are now routinely produced around the world provides an opportunity for assessing uncertainties in HC and quasi-real time monitoring of this variable using the ensemble methodology. The spread of the ensemble can also be used as a measure of HC uncertainties, and it may also help to identify gaps in observing systems, and deficiencies in data assimilation schemes. Towards this goal we analyzed ten ORAs, two objective analyses

based on in situ data only (EN3, NODC) and eight model analyses based on ocean data assimilation systems (GODAS, CFSR, GFDL, GMAO, ECMWF, JMA, BOM, MERCATOR).

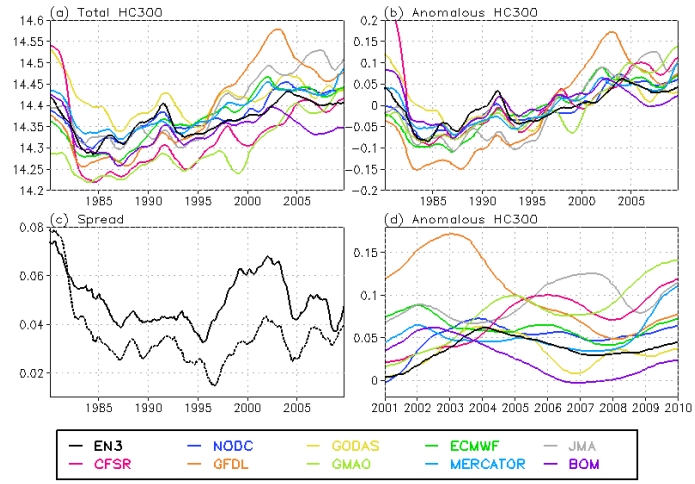

Fig. 2. Time series of one-year running mean of (a) total HC300, and (b), (d) anomalous HC300 averaged in 70°S-70°N, (c) spread of total HC300 (solid line) and anomalous HC300 (dash line).

The mean, annual cycle, interannual variability and long-term trend of upper 300m HC (HC300) from 1980 to 2009 was compared. Results were reported in a paper submitted in Journal of Climate (Xue et al. 2012). Dr. Xue gave an oral presentation of this work at the WCRP Open Science meeting in Denver on October 24-28, 2011.

Outcome of the task 3.1.2, i.e., quantifying observational uncertainties in the analysis of upper ocean heat content, addressed the OCO program deliverable #2.

<u>2.1.4. Comparing CFSR with measurements from the OceanSites:</u> In FY11 we initiated a task to compare the in situ measurements from the Kuroshio Extension Observatory (KEO) ocean reference buoys with the CFSR analysis. The work is in collaboration with Dr. Megahn Cronin at the PMEL. We will present primary results of this work at the 4th WCRP International Conference on Reanalyses in Washington D.C. on May 7-12, 2012.

Outcome of the task 3.1.3. will enhance the utility of the OceanSite measurements that are supported by the COD, and thereby, support the COD program deliverable #3.

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

The goal of the task would be to maintain an ocean data assimilation capability that could be used for Observing System Experiments (OSEs). As part of this task we have acquired the latest GODAS_MOM4 system, which is also the oceanic component of the CFSR. With this system, we have finished five experimental runs in which temperature profiles from XBT, TAO and Argo were selectively assimilated (see Table 1 for summary).

Pentad temperature from the five experimental runs was validated against TAO observations. Root-mean-square error (RMSE) from TAO temperature was calculated and averaged over the

top 300m at four buoy sites, 170°W, 140°W, 125°W and 95°W. We found that RMSE increased from STD to nTAO significantly in 1990s and early 2000s, but changed little after 2004 when Argo data were assimilated.

Data assimilated	**CTL** (no Ocean Data) (1990-2008)	**STD** (all Ocean Data) (1990-2008)	**nTAO** (All Ocean Data Except TAO) (1990-2008)	**nArgo** (all Ocean data except Argo) (1999-2008)	**nTAO_nArgo** (all ocean data except TAO and Argo) (1999-2008)
XBT	×	√	√	√	√
TAO	×	√	×	√	×
Argo	×	√	√	×	×

Table 1. Experiment runs conducted with GODAS_MOM4 system in which various observations (XBT, TAO and Argo) were selectively assimilated (√) or not assimilated (×).

The impacts of Argo observations on RMSE were mostly confined to the 2004-2008 period when Argo data are most plentiful. RMSE increased from STD to nArgo by more than 80% poleward of 5°N and 5°S. This result suggests that Argo data plays critical roles in constraining model errors off the equator. Therefore, we conclude that TAO and Argo data are complimentary to each other in terms of constraining model errors. Without both TAO and Argo data, RMSE would have increased by more than 80% east of 130°W in the eastern tropical Pacific, where accuracy of subsurface ocean temperature initialization plays critical roles in ENSO prediction. Results will be reported in a peer reviewed journal.

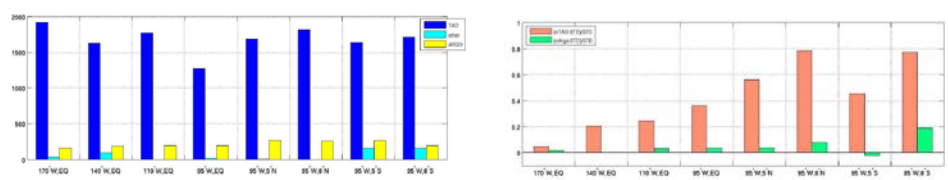

Fig. 3. (a) Number of daily profiles from TAO (dark blue), Argo (yellow) and XBT (light blue) near TAO buoy sites during 2004-2008. (b) Percentage of increase in RMSE from STD to nTAO (orange) and from STD to nArgo (green) in 2004-2008

3.3 Sub-Task 3: Global oceanic precipitation analysis in support of understanding air-sea exchange of fresh water and its influence on surface salinity

All three projects (3.3.1-3.3.2) under this task relate to improving the analysis of fresh water flux into the ocean, and understanding its relationship with changes in the surface salinity. Objectives of this sub-task, therefore, addressed the COD program deliverable # 3

3.3.1 CMORPH high-resolution global precipitation analysis: CMORPH, a CPC product, is capable of depicting global precipitation variations on a very high spatial (8km x 8km) and temporal (30-min) resolution. During FY11, we extended the CMORPH precipitation analyses back to January1998 and reprocessed the CMORPH from 2003 and 2004 for improved homogeneity. We then adjusted the bias in the raw CMORPH satellite estimates against a long-term and homogeneous precipitation data set so that the resulting adjusted high-resolution CMORPH satellite estimates may be utilized from a climate perspective.

Using the bias-adjusted high-resolution CMORPH global precipitation estimates, we examined global oceanic precipitation variations as depicted in the observations and in the three sets of new generation reanalyses, i.e., the CFS reanalysis (CFSR), MERRA, and the ERA Interim. In particular, we investigated the diurnal cycle of the global oceanic precipitation, taking advantage of the high temporal resolution (30-min) of our CMORPH satellite estimates. As illustrated in Fig. 4, the diurnal cycle of the precipitation is reasonably well reproduced by the reanalyses over many global regions. A paper describing the global precipitation diurnal cycle and its representation in the three sets of reanalyses is being drafted.

3.3.2 CMAP global precipitation analysis: CMAP data set provides an extended record of monthly and pentad (5-day) precipitation on a 2.5^{o}lat/lon over the globe from 1979 to the present. This part of our project involves two components: routine updates of the CMAP data sets and the examination of oceanic precipitation using CMAP data sets. The CMAP precipitation analyses have been updated routinely and made available to the science community and general public through the CPC ftp server (ftp.cpc.ncep.noaa.gov/precip). As of Jan.2012, the monthly and pentad CMAP analyses are updated to the end of November 2011. The CMAP data sets are widely used by a variety of users in oceanic and climate studies, health management, and water resources management. CMAP data sets provide critical information for the monitoring of oceanic fresh water fluxes.

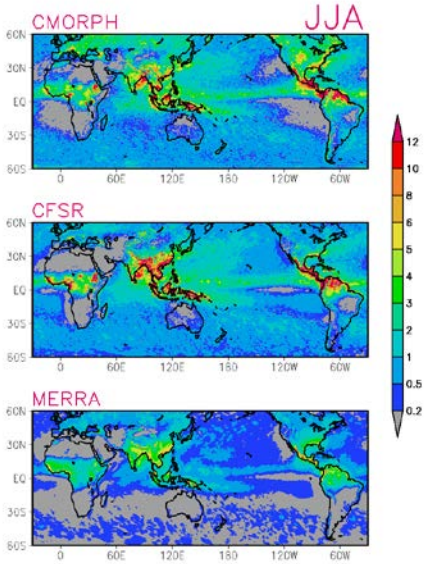

Fig.4: Diurnal amplitude (mm/day) for June-July-August, defined as the standard deviation of 24 hourly precipitation averaged for the season for 1998 to 2010, derived from the bias adjust CMORPH satellite estimates (top), CFR reanalysis (middle), and MERRA (bottom).

3.3.3 Comparison of P-E with changes in salinity: With the successful launch of the NASA Aquarius satellite, we have succeeded in examining the quantitative relationship between the satellite observed sea surface salinity (SSS) and the oceanic fresh water flux (P-E) derived from the bias-adjusted CMORPH satellite precipitation estimates and the evaporation from the CFS

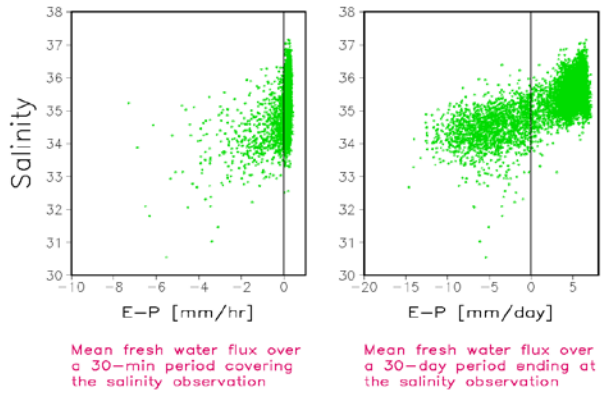

Fig. 5: Scatter plots of Instantaneous sea surface salinity (SSS) observed by the NASA Aquarius satellite and the fresh water flux (P-E) accumulated over a 30-minute (left) and 30-day (right) period prior to the SSS observation. The scatter plots are for areal mean SSS and P-E over central Pacific [180°-160°W; 10°S-10°N] for a data period of 68 days from August 25 to October 31, 2011.

reanalysis. In particular, the high resolution of both the CMORPH and the CFS reanalysis enable a comprehensive investigation of the SSS and (P-E) relationship at a spectrum of time scales from 30 minutes to 30 days. As shown in Fig. 5, variations of sea surface salinity (SSS) are largely influenced by the fresh water flux over open oceans. SSS observed by the Aquarius appears in good linear relationship with the fresh water flux, especially for longer accumulation period.

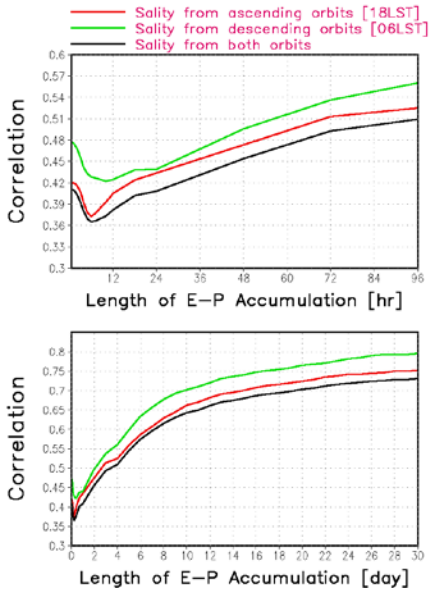

Fig. 6: Correlation between Aquarius-observed instantaneous sea surface salinity (SSS) and fresh water flux (P-E) accumulated over a time period of 30-minutes to 30 days prior to the SSS observation. Fresh water flux is computed using 30-min precipitation from the bias-adjusted CMORPH and the evaporation data from the CFS reanalysis. Correlation is computed for data pairs of SSS and P-E averaged over grid boxes of 1°lat/lon over central Pacific [180°-160°W; 10°S-10°N] and for a 68 days from August 25 to October 31, 2011.

Quantitative analysis showed that the correlation between the Aquarius observed SSS and the fresh water flux first decreases with the length of the accumulation period for the fresh water flux from 30 minutes to several hours (Fig.5, top). The correlation then bounces back with the accumulation time and reaches to a table level of ~0.75 for the fresh water flux accumulated over a period of 15 days or longer. The opposite trends of correlation changes imply the involvements of different mechanisms in the fresh water forcing to the salinity variations. A paper describing this new finding is being drafted for publication at Geophysical Research Letter. Further work is underway to quantify the SSS and fresh water relationship over various regions of the global ocean and for different seasons using data for a longer period. Noteworthy mentioning here is the critical importance of the high time resolution CMORPH precipitation estimates. The correlation dip in the SSS – fresh water flux correlation would not be detected using a data set of coarser resolution.

4. Education and Outreach

4.1 Ocean Products

We served a broad user community for our global ocean monitoring products. Through our "Monthly Ocean Briefing" (MOB) we continued to maintain a routine email exchange with many users and participants. Following are a few examples signifying the impact of deliverables under this project:

- The MOB has been routinely attended by colleagues from the NOAA Fisheries Service. Because of our experiences in monitoring ENSO, PDO and coastal upwelling, Dr. Xue has been invited by the Southwest Fisheries Science Center, to contribute to the CalCOFI Annual Report (http://www.calcofi.org), and to contribute to the PaCOOS (www.pacoos.org) Annual Newsletter on "Physical and Ecological Conditions in the California Current Large Marine Ecosystem" since 2009;
- Dr. Xue has worked with the ocean expert team of NOAA in the preparation of the Ocean Chapter for the BAMS Annual Climate Report. Dr. Xue is also the first author for the global SST Section in the BAMS Annual Climate Report in the past two years.
- The ocean plots from "Monthly Ocean Briefing" and "Annual Ocean Review" have been widely used by many users in private sectors, operational centers and academic institutions (the ocean expert team of NOAA, Dr. Klaus Weickmann, Dr. Frank Schwing, Dr. David Enfield, Dr. Nick Bond, Dr. Kevin Trenberth, Dr. Bohua Huang, Dr. David Dewitt, Dr. Tony Rosati, Dr. Mike McPhaden, Dr. Chunzai Wang, Dr. Weidong Yu).

The work conducted as part of this proposal has been reported in various peer reviewed journals, conferences, and workshops.

4.2 Precipitation Products

Two primary deliverables of this project are the CMAP and CMORPH precipitation analyses. The low-resolution, long-term (from 1979) CMAP data set is widely used in operations for the monitoring of global precipitation and in research to examine climate variability and air-sea interactions, and to force oceanic models. Two papers describing the CMAP data set have

been cited by more than 2000 papers. Mean climatology of global precipitation derived from CMAP has been used in text books for graduate and college students.

The CMORPH precipitation data set for modern era (from 1998) provides critical information for precipitation variations on high spatial and temporal resolution. It is utilized by forecasters to monitor and predict severe weather systems over both land and coastal regions and by managers in both public and private sectors around the world for the monitoring of potential coastal hazards. The CMORPH data set is also used by colleges as educational materials for weather and climate. As demonstrated in our preliminary work with the Aquarius SSS data, the high-resolution CMORPH satellite precipitation data enables the investigation of global ocean and its interaction with climate from a spectrum of new perspectives.

The research work supported by this project provides refined oceanic precipitation analyses and improved understanding of air-sea fresh water exchanges and their relation to salinity that are important components of the ocean – climate connections. Verification of the fresh water fluxes produced by NOAA climate models and reanalyses using observation data sets leads to the improvements of these operational tools.

4.2.3. Relevant websites for dissemination of information

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

5. Publications and Reports

5.1. Publications by Principal Investigators

Publications in Journals:

Xue, Y., and Co-authors, 2012a: A Comparative Analysis of Upper Ocean Heat Content Variability from an Ensemble of Operational Ocean Reanalyses. *J. Climate*, conditionally accepted.

Wen, C., Y. Xue, and A. Kumar, 2012: Ocean-Atmosphere characteristics of Tropical Instability Waves Simulated in the NCEP Climate Forecast System Reanalysis. *J. Climate*, conditionally accepted.

Wen, C., Y. Xue, and A. Kumar, 2012: Seasonal Prediction of North Pacific SSTs and PDO in the NCEP CFS Hindcasts. *J. Climate*. conditionally accepted

Guilyardi, C., and Co-authors, 2012: New strategies for evaluating ENSO processes in climate models. *Bull. Amer. Meteor. Soc.*, to appear.

Kumar, A., and Co-authors, 2012: Evolving Observing System, Coupled Initialization, and Their Influence on Seasonal Climate Prediction in the NCEP CFS. *Mon. Wea. Rev.*, conditionally accepted.

Huang, B., Y. Xue, A. Kumar, and D. Behringer, 2012: AMOC variations in 1979-2009 simulated by the NCEP operational ocean data assimilation system. *Climate Dynamics*, to appear.

Huang, B., Z.-Z. Hu, E. K. Schneider, Z. Wu, Y. Xue, B. Klinger, 2012: Influences of Subtropical Air-Sea Interaction on the Multidecadal AMOC Variability in the NCEP Climate Forecast System, *Climate Dynmics*, to appear.

Wang, W., M. Chen, A. Kumar, Y. Xue, 2011: How important is intraseasonal surface wind variability to real-time ENSO prediction? *Geophys. Res. Lett*., **38**, L13705, doi:10.1029/2011GL047684.

Xue, Y., R. W. Reynolds, V. Banzon, T. Smith, and N. Rayner, 2011: Global oceans: Sea surface temperature. In State of the Climate in 2010, D.S. Arndt, M.O. Baringer and M.R. Johnson, eds., *Bull. Amer. Meteorol. Soc*..

Xue, Y., and Co-authors, 2011: An Assessment of Oceanic Variability in the NCEP Climate Forecast System Reanalysis. *Climate Dynamics*, **37**, 2511–2539, DOI 10.1007/s00382-010-0954-4.

Joyce, R.J., and P. Xie, 2011: Kalman Filter Based CMORPH, *J. Hydrometeor.*, **12**, 1547 – 1563, DOI: 10.1175/JHM-D-11-022.1.

Xie, P., R.J. Joyce, Y.Xue, W.Wang, and A. Kumar, 2012: Sea Surface Salinity and Fresh Water Flux Relationship: A First Look at the Aquarius Data. To be submitted to *Geophys. Res. Lett.*

Workshops and conference presentations:

Xue, Y., and Co-authors, 2011: A Comparative Analysis of Upper Ocean Heat Content Variability from an Ensemble of Operational Ocean Reanalyses. WCRP Open Science Conference, October 23-28, 2011, Denver, CO.

Xue, Y., and Co-authors, 2011: Operational Ocean Climate Indices from an Ensemble of Operational Ocean Reanalyses. GODAE OceanView-GSOP-CLIVAR workshop, June 13-17, 2011, Santa Cruz, CA.

Kumar, A., 2011: ENSO observation, theory, and change: WGSIP perspective. CLIVAR workshop on New strategies for evaluating ENSO processes in climate models. Paris, France, 17-19 November 2010.

Xie, P., S.-H. Yoo, W.Wang, A. Kumar, L.Zhang, and W. Ebisuzaki, 2011: Global Precipitation Diurnal Variatiosn Depicted in the Observations and Reanalyses. 36th Annual Climate Diag. & Pred. Workshop, October 3-6, 2011, Fort Worth, TX.

Xie, P., S.-H. Yoo, and A. Kumar: 2011: Observed Climate: A High-Resolution Real-Time Analysis of Global Oceanic Precipitation. WCRP Open Science Conference. October 17 – 21, 2011, Denver, CO.

5.2. Other Relevant Publications

1. A figure from Xue, Y., and Co-authors, 2011: An Assessment of Oceanic Variability in the NCEP Climate Forecast System Reanalysis. *Climate Dynamics*, **37**, 2511–2539, DOI 10.1007/s00382-010-0954-4, has been included in the Chapter 3 of WG1 of the IPCC AR5 report that will be released in 2013.