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 the global climate variability influencing various facets of society. The ocean's control on atmosphere extends from weather to climate on seasonal, decadal and centennial time-scale. Oceans are also an important source of societal well-being, e.g., food security, transportation, prediction of droughts and floods etc. Due to their large thermal inertia, and a spatial coverage of ~70% 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 information and data sets to the user community to (a) provide a scientific basis to make informed decisions to either mitigate or to take advantage of the consequences resulting from the ocean climate variability (e.g., El Niño-Southern Oscillation), (b) enable science and improve 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 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. Scientific Accomplishments

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

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

(a) Maintenance of the Global Ocean Data Assimilation System (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 view of the current state of the ocean. In FY12, we monitored all the products on our website to ensure they were appropriately updated and were 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 sea surface temperature (SST) predictions through the "Monthly Ocean Briefing" (MOB). The format for the MOB includes a community conference call and PowerPoint presentation (PPT), and is held around the 7th day of the month. The archive of the ocean briefing PPTs since May 2007, as well as the real time plots that are in the PPTs, can be accessed through the website.

In FY12, we developed new products for the monthly ocean briefings, and for ocean climate monitoring:

- Ensemble predictions for ENSO, Pacific Decadal Oscillation (PDO), Indian Ocean Dipole (IOD) and tropical North Atlantic SST from NCEP CFSv2 model;
- Recent three month evolutions of anomalous SST, surface winds, seal level pressure, surface heat fluxes and outgoing longwave radiation (OLR) in each ocean basin;
- Recent three month evolutions of depth of 20C isotherm anomalies and comparison with previous year;
- Relationship between SST change and net surface heat fluxes into the ocean
- SST anomaly indices based on the 1981-2010 climatology and recent 10 year climatology to distinguish interannual variability from long-term changes;
- SST anomaly indices for different flavors of ENSO (ENSO Modoki, Warm Pool and Cold Tongue SST indices)

The GODAS website provides access to the ocean analysis data sets and numerous plots of various oceanic variables from January 1979 to the present, and the archive of ocean briefing PPTs. We monitor the number of monthly hits on the GODAS website by the public and use it as a performance measure for the public usage of our ocean monitoring products. Fig.1 shows that the number of monthly hits increased by 60%, from about 55,000 to 90,000, around December 2011, and stabilized at the higher level since then.

(b) Maintain "Annual Ocean Review" and lead the SST section in the Ocean Chapter of the BAMS Annual Climate Report: In early February 2012, we prepared an "Annual Ocean Review" (AOR) to summarize the major features of the state of global oceans in 2011. 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. Our AOR plots can be readily used by others in preparation of their sections in the Ocean Chapter.

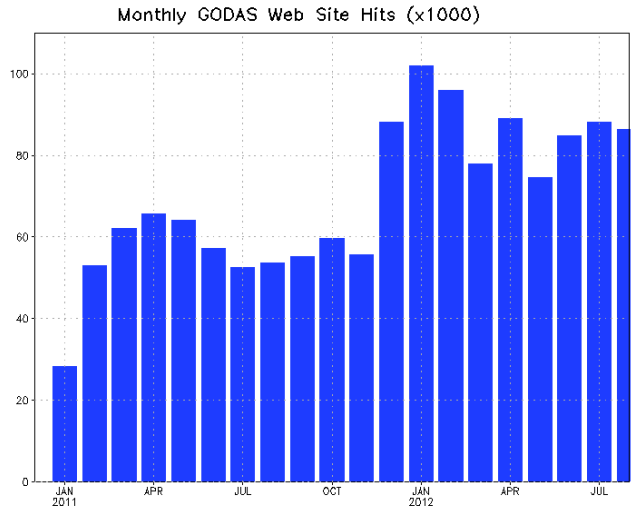

Fig. 1. Number of monthly hits on the GODAS website from January 2011 to August 2012.

We led the SST section in the Ocean Chapter. By including two new coauthors in this year's annual report, we improved our analysis of global SST variability by providing a summary of global SST variations in 2011 with emphasis on the recent evolutions of ENSO and PDO, and also placing the 2011 SST in the context of the historical record since 1950. In addition, we shared our plots of the SST section to assist others in preparation of their sections on ocean variables that are strongly influenced by SST (i.e. ocean surface fluxes and ocean colors).

<u>(c) Comparative analysis of upper ocean heat content from an ensemble of operational ocean analyses:</u> The availability of multiple operational ocean analyses (ORA) that are now routinely produced around the world provides an opportunity for assessing uncertainties in ocean heat content (HC) and quasi-real time monitoring using the ensemble methodology. As a first step, we analyzed ten ORAs. The results are summarized in the paper Xue et al. (2012) recently published in J. Climate. In addition, Dr. Yan Xue gave an oral presentation on this topic at the *WCRP Open Science Meeting*, Denver, CO, in October 23-28, 2011, and *WCRP 4th Reanalysis Conference*, Silver Spring, MD, in May 7-11, 2012.

<u>(d) Comparing CFSR with measurements from the OceanSites:</u> In the North Pacific, intense air-sea interactions near Kuoshio Extension can affect the weather and climate locally and remotely, and thus are critical to the global climate system. The NCEP CFSR represents a new high resolution reanalysis effort having a potential to capture surface heat fluxes well. The Kuroshio Extension Observatory buoy site (KEO), an ocean reference site, provides high-quality independent air-sea flux time series for validation. In FY12, we collaborated with Dr. Megahn Cronin at the PMEL, and initiated a task to validate the CFSR fluxes against the KEO data. The purpose of this study is to (1) evaluate the extent to which surface heat fluxes from the CFSR agree with the KEO buoy data, and to (2) provide recommendations of surface heat flux quality control for the next generation of NCEP reanalysis product. Our results suggest that the temporal

variations of latent and sensible heat fluxes are highly consistent between the CFSR and KEO time series. The bias and the root mean square (RMS) errors in the CFSR are substantially lower than earlier NCEP reanalysis data (e.g., R1 & R2). For example, the bias in the net surface heat flux in the CFSR is about 22 W/m^2, which is much smaller than that in R1 (49 W/m^2) and R2 (56 W/m^2). The outcome of this project will enhance the utility of the OceanSite measurements that are supported by the COD

Table 1 Validation of shortwave radiation (SWR), longwave radiation (LWR), latent heat flux (LHF), sensible heat flux (SHF) and total heat fluxes (THF) of the CFSR, R1 and R2 against KEO data.

	SWR			**LWR**			**LHF**			**SHF**			**THF**		
	CFSR	R1	R2	CFSR	R1	R2	CFSR	R1	R2	CFSR	R1	R2	CFSR	R1	R2
Correlation	0.87	0.8	0.88	0.8	0.8	0.8	0.97	0.92	0.9	0.97	0.93	0.94	0.97	0.93	0.94
RMS	43.6	48	38	14.5	15	15	38.1	48	62	10.9	20	23	54.8	77	85
Bias	6.4	-1	5	2.4	1	-6	24	38	60	1.1	9	7	-22	49	56

Outcome of the sub-task address following COD program deliverables: # 1 - identify significant patterns of climate variability and change; #2 – monitoring of the heat content of the ocean; and #3 – monitor Air-Sea Exchanges of Heat, Momentum, and Fresh Water, to identify changes in forcing functions

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 has been to maintain an ocean data assimilation capability that could be used for Observing System Experiments (OSEs), e.g., influence of TAO on ocean monitoring and prediction. As part of this task we acquired the latest GODAS_MOM4p0 system, which is also the oceanic component of the CFSR. With this system, we finished five experimental runs in which temperature profiles from XBT, TAO and Argo were selectively assimilated and the preliminary results were reported in the last year progress report. However, the works was discontinued when the Vapor super computer at NCEP was phased out in spring 2012.

Since summer 2012, we started to work on the GODAS_MOM4p1 system, which was recently installed on the new NOAA Gaea high performance computing. As a first step, we conducted a control run in which the MOM4p1 ocean model was forced by the NCEP Reanalysis 2 surface fluxes and no observations were assimilated. The differences between the control run and operational GODAS show the impacts of data assimilation. Fig. 2 shows that without data assimilation the model heat content is generally too high in the tropical Indian and Atlantic Ocean. For the tropical Pacific, the model simulates the ocean heat content in the western Pacific reasonably well, but has warm bias in the equatorial eastern Pacific where the model thermocline is too diffuse, particularly during ENSO-neutral and La Nina years (upper right panel). Therefore, data assimilation during ENSO-neutral and La Nina years is particularly important to correct the model systematic bias in the eastern Pacific.

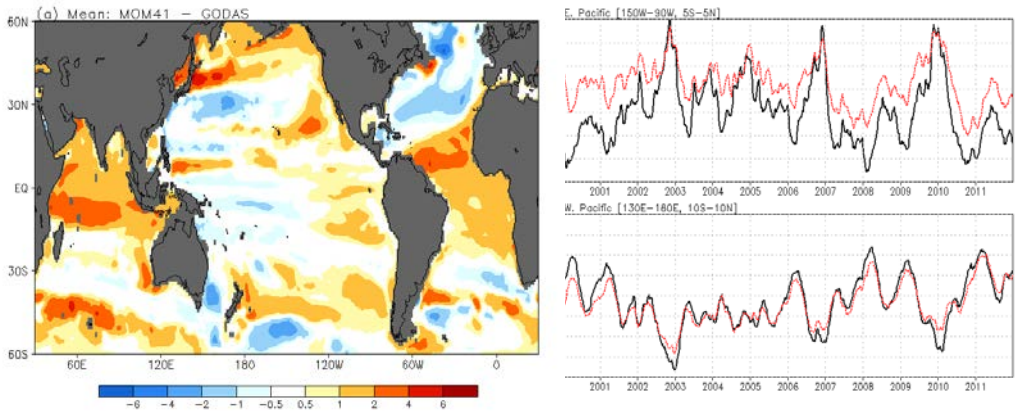

Fig. 2. Upper 300m ocean heat content (HC300). (left) Mean HC300 difference between the MOM4p1 control run and operational GODAS in 2004-2011; (right) HC300 average in the equatorial eastern Pacific (150°W-90°W,5°S-5°N, upper panel) and the tropical western Pacific (130°E-180°E,10°S-10°N, lower panel) for GODAS (black) and MOM4p1 (red).

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

All three projects 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

<u>(a) CMORPH high-resolution global precipitation analysis:</u> 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 FY12, we continued our efforts to extend and process the CMORPH precipitation analyses using a frozen algorithm and the same versions of inputs for the entire period from January 1998 to the present. We then adjusted the bias in the reprocessed 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. The reprocessed and bias corrected CMORPH high-resolution global precipitation data sets are being released right now. (The data release was delayed by several months due to the IT restrictions caused by the relocation of our office building.). A paper describing the product suite is currently under preparation.

<u>(b) CMAP global precipitation analysis:</u> 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. Preliminary investigation has been conducted to examine the best strategy for the construction of the next generation CMAP precipitation analyses on a 0.25^{o}lat/lon grid over the globe and on a time resolution of 3-hourly (or daily) covering an extended period from 1979 to the present. In particular, we experimented with a technique to derive precipitation estimates from infrared (IR) observations from

geostationary and polar orbiting satellites through matching the probability density function (PDF) of the IR brightness temperature to that of the precipitation rates from the passive microwave (PMW) satellite observations. As illustrated in Fig. 3, the IR-based precipitation estimates (right) has a very similar spatial patterns with those from the PMW estimates (left). Since the high-quality PMW precipitation estimates are only available from July 1987 and the satellite observations started from 1978 and earlier, the combined use of IR-based precipitation estimates and the PMW precipitation data will enable the construction of a global oceanic precipitation estimates with improved time / space resolution and relatively homogeneous data quality over the entire data period from 1979 to the present. Further work is underway to refine the IR-based technique for massive production for the target data period.

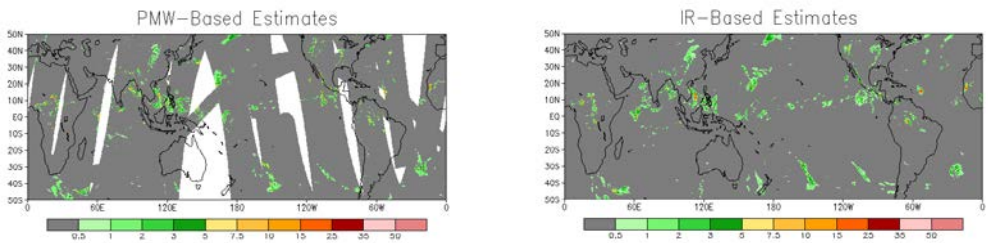

Fig.3: Global three-hourly precipitation rate (mm/hr) for 00-03Z, 1 September, 2012, derived from the passive microwave retrievals (left) and the geostationary IR observations (right).

<u>(c) Construction of a blended analysis of sea surface salinity (SSS)</u>: In FY12, we have developed a prototype algorithm to construct an analysis of sea surface salinity (SSS) on a 1°lat/lon grid over the global ocean through blending information from the in situ measurements and retrievals from recently launched NASA Aquarius and European Space Agency (ESA) Soil Moisture Oceanic Salinity (SMOS) satellites. Biases in the satellite retrievals are first removed through matching the probability density function (PDF) of the satellite salinity against that of the in situ measurements. The bias-corrected satellite retrievals were then combined with the in situ measurements through an optimal interpolation (OI), in which the monthly SSS anomaly from the previous time step is used as the first guess, while the in situ and satellite data are employed to refine the first guess fields. The blended SSS analysis was constructed for a 6-month period from September 2011 to February 2012 and compared with an in situ based SSS analysis created by NODC. Preliminary results demonstrated that the blended SSS analysis, with additional information from satellite observations, is capable of capturing SSS variations of fine spatial structures that are missed in the in situ measurements (Fig.4). A paper describing the prototype SSS blending algorithm is under drafting. Further work is underway to fine tune the algorithm and to construct the blended SSS analysis for a three year period from January 2010 to the present.

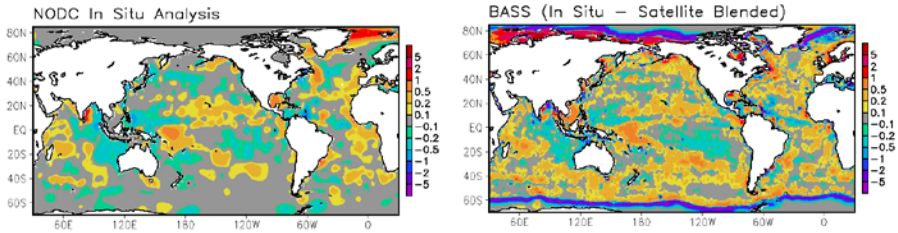

Fig. 4: Anomaly of global sea surface salinity (SSS, PSU) for October 2011, derived from the NODC in situ based analysis (left) and the prototype NOAA Blended Analysis of Surface Salinity (BASS, right).

(d) Diagnostic study of SSS - fresh water flux relationship: We have started to diagnose the relationship between the fresh water flux and the sea surface salinity, taking advantage of the blended SSS analysis described in section 2.3.2. Due to the delay in the delivery of satellite SSS retrievals from NESDIS/STAR (also caused by the office building relocation), we were only able to construct the prototype global SSS analysis only for a relatively short period of time (6 months). In addition, observation-based evaporation data sets (e.g. the OAFlux) were not available for the SSS data period for the purpose of validation. Our preliminary study on this aspect is therefore targeted on the collection of related data sets and a qualitative comparison of the SSS with the oceanic precipitation fields derived from our CMORPH satellite estimates. As shown in Fig.5, quite good correspondence is found between the SSS and precipitation anomaly fields over equatorial Pacific and other tropical oceanic areas where ITCZ brings in heavy amount of precipitation that dominate the fresh water flux. Relationship between SSS and precipitation, however, is less clear over other regions where evaporations, ocean currents and the river runoffs play important roles. We will continue this study after we finish the construction of the SSS for the recent three years.

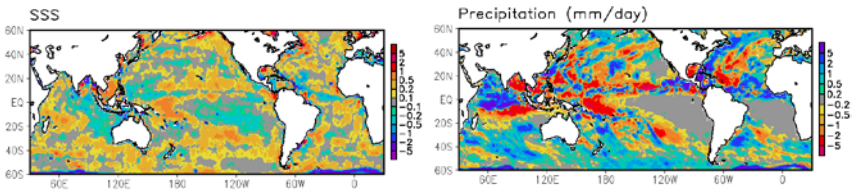

Fig. 5: Anomaly of global sea surface salinity (SSS, left) and precipitation (mm/day, right) for October 2011.

2.1 Education and Outreach

(a) 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 many users and participants. Following are a few examples signifying the impact of deliverables under this project:

- The ocean briefing has been attended by many colleagues from NOAA and academia (the ocean expert team of NOAA, Dr. David Legler, Dr. Diane Stanitski, Dr. Klaus Weickmann, Dr. Frank Schwing, Dr. David Enfield, Dr. Nick Bond, Dr. Kevin Trenberth, Dr. Tim Boyer, Dr. Syd Levitus, Dr. Dick Crout, Dr. Richard Bouchard, Dr. Bohua Huang, Dr. David Dewitt, Dr. Tony Rosati, Dr. Michele.m Rienecker, Dr. Mike McPhaden, Dr. Chunzai Wang, Dr. Weidong Yu).

- The ocean briefing plots have been used by a broad user community in private sectors, operational centers, and academic institutions. Particularly, those plots have been used as teaching materials for high school, college and graduate students.
- The ocean briefing plots are also routinely used by CPC's operational predictions, e.g. ENSO prediction, Atlantic hurricane seasonal prediction and seasonal predictions for U.S. temperature and precipitation, and they are also used by the Intra-Americas Study of Climate Processes (IASCLiP) Forecast Forum (http://www.eol.ucar.edu/projects/iasclip).
- The "Annual Ocean Review" plots are used by the ocean expert team of NOAA in the preparation of the Ocean Chapter in the BAMS Annual Climate Report.

The research works supported by this project have 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, and studies of prediction skill and predictability of ENSO and PDO.

(b) Precipitation Products

Two primary deliverables of this component 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.

(c) 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/

3. Publications and Reports

3.1. Publications by principal investigators

Publications in Journals:

Published:

Xue, Y., **Z.-Z. Hu, A. Kumar**, V. Banzon, T. Smith, and N. Rayner, **2012**: Global oceans: Sea surface temperature. In State of the Climate in 2011, Bull. Amer. Meteorol. Soc.. J. Blunden and D.S. Arndt, eds., *Bull. Amer. Meteorol. Soc.*. **93**, S57-S62.

Kumar, A. M. Chen, L. Zhang, W. Wang, **Y. Xue**, C. Wen, L. Marx, and B. Huang, **2012**: An Analysis of the Non-stationarity in the Bias of Sea Surface Temperature Forecasts for the NCEP Climate Forecast System (CFS) Version 2. *Mon. Wea. Rev*.. **140**, 3003-3016.

Wen, C., **Y. Xue**, and **A. Kumar**, **2012**: Seasonal Prediction of North Pacific SSTs and PDO in the NCEP CFS Hindcasts. *J. Climate*, **25**, 5689–5710.

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*, **25**, 6409–6425.

Xue, Y., M. A., Balmaseda, T. Boyer, N. Ferry, S. Good, I. Ishikawa, **A. Kumar**, M. Rienecker, T. Rosati, Y. Yin, **2012**: A comparative analysis of upper ocean heat content variability from an ensemble of operational ocean reanalyses, *J. Climate*, **25**, 6905-6929.

Guilyardi, C., and Co-authors (including **A. Kumar**), 2012: New strategies for evaluating ENSO processes in climate models. *Bull. Amer. Meteor. Soc.*, **93**, 235-238.

Huang, B., **Y. Xue**, **A. Kumar**, and D. Behringer, **2012**: AMOC variations in 1979-2008 simulated by NCEP operational global ocean data assimilation system. *Clim. Dyn*., **38**, 513-525.

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. *Clim. Dyn*., **39**, 531-555.

In Press:

Kumar, A., H. Wang, W. Wang, **Y. Xue**, and Z.-Z. Hu, **2012**: Does Knowing the Oceanic PDO Phase Help Predict the Atmospheric Anomalies in Subsequent Months? *J. Climate.* to appear.

Hu, Z.-Z., **A. Kumar**, H.-L. Ren, H. Wang, M. L'Heureux, and F.-F. Jin, 2012: Weakened interannual variability in the tropical Pacific ocean since 2000. J. Climate, to appear.

In revision:

Xue, Y., M. Chen, **A. Kumar, Z.-Z. Hu**, W. Wang, **2012**: Prediction Skill and Bias of Tropical Pacific Sea Surface Temperatures in the NCEP Climate Forecast System Version 2. *J. Climate*. Conditionally accepted.

Submitted:

Kumar, A., L. Zhang, and W. Wang, 2012: Sea Surface Temperature - Precipitation Relationship in Different Reanalyses. Mon. Wea. Rev., conditionally accepted.

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, 2012: A Comparative Analysis of Upper Ocean Heat Content Variability from an Ensemble of Operational Ocean Reanalyses. *WCRP 4th Reanalysis Conference*, Silver Spring, MD, May 7-11, 2012.

3.2. Other relevant publications

1. A figure from Xue, Y., and Co-authors, 2012: An Assessment of Oceanic Variability in the NCEP Climate Forecast System Reanalysis. *Clim. Dyn.*, **37**, 2511–2539, has been included in the Chapter 3 of the IPCC AR5 report that will be released in 2013.