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 Office of Climate Observations (OCO) and the Climate Prediction Center (CPC) and focuses 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 OCO. The ocean products *disseminated* as part of this project provide a *synthesis of the state of the global oceans, and 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.

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 (e.g., intensification of hurricanes and tropical storms), to seasonal climate variability [e.g., the influence of sea surface temperature changes in the tropical eastern Pacific related to El Nino – Southern Oscillation (ENSO) on global climate], and to climate variability and change on decadal and centennial time scales. Oceans themselves are 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, oceans are also a key to monitoring and understanding the influence of human induced change in the Earth system, and are the place where such influences would be detected with confidence.

Given the importance of ocean climate variability, monitoring its current state, its real-time evolution, and understanding causes for climate variability is of crucial importance. *The outcomes of this project supported by the OCO - disseminating a synthesis of the state of the global oceans* - provide the essential information to the user community that is being currently 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 about the slowly evolving changes in the ocean state. The importance of this project underpinned by the fact that raw ocean observations can seldom be ingested by the user community, and it is the process of converting individual observations into a synthesis in a form that could be easily understood, and having a dissemination system, is what is required for an end-to-end ocean climate information system. Further, such an ocean climate information system is envisioned to be an integral component of the emerging NOAA's Climate Service (NCS).

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 developed based 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 of the oceans climate variability from intraseasonal to interannual to decadal and long-term 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 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 of natural escalation in costs (e.g., ship time; cost of hardware etc.), and (b) recent advances in the observing system, e.g., ARGO profiles, that provide additional observations and 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 be able to examine the fresh water flux used as a forcing in the NCEP Global Oceanic Data Assimilation System (GODAS), and to compare P-E 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 Development of a real-time heat budget monitoring and analysis system for the ENSO: We developed and implemented a real-time heat budget analysis for ENSO based on GODAS. The methodology for heat budget analysis has been summarized in a journal paper (Huang et al. 2009). The heat budget analysis of the ocean mixed-layer variability not only helps us understand the physical mechanism for the past ENSO events, and but also assists in monitoring, understanding, and predicting ENSO in real time. For example, Fig. 1 shows the heat budget evolution for the current 09/10 El Nino. It suggests that zonal advection contributed to the decay of the 08/09 La Nina during the early spring 09, and both zonal advection and vertical entrainment and diffusion contributed to the fast development of the 09/10 El Nino during March-June 2009. The monitoring of the heat budget of the oceanic mixed layer also highlights the impacts of oceanic Kelvin waves on intraseasonal variability of mixed layer temperature during July-October 2009. The real-time heat budget analysis for ENSO is a valuable addition to the suite of ENSO monitoring products maintained by CPC. The heat budget product has been introduced to the public in a Community White Paper by Xue et al. 2009 in the OceanObs09 Meeting, and in a Climate Test Bed seminar on November 19, 2009 (ftp://ftp.cpc.ncep.noaa.gov/CTB/2009-2010).

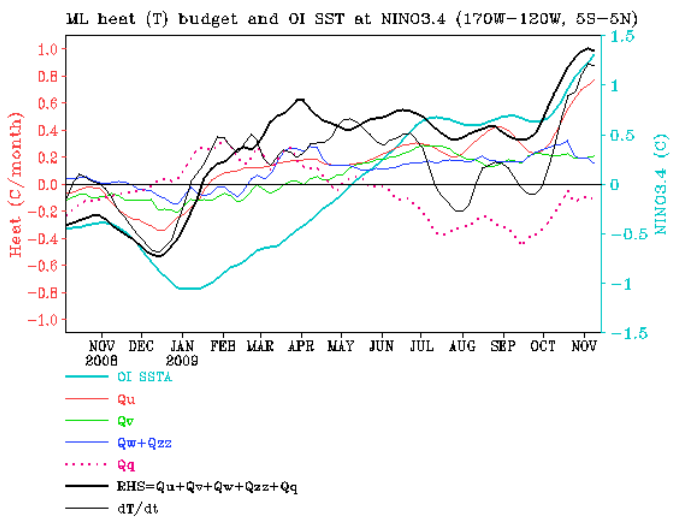

Fig. 1. The recent evolution of the NINO3.4 SST anomaly and different heat budget terms averaged in the NINO3.4 region. Qu: zonal advection; Qv: meridional advection; Qw: vertical entrainment; Qzz: vertical diffusion; Qq: adjusted net heat fluxes including solar penetration; dT/dt: tendency of mixed layer temperature; RHS: sum of all heat budget terms

3.1.2. Monitoring and comparison of upper ocean heat content variability: Upper ocean heat content (UOHC) is one of the key indicators of climate variability on many time-scales extending from interannual to long-term anthropogenic trends. Since UOHC variability is also associated with SST variability, a better understanding and monitoring of UOHC variability can help us understand, monitor, and forecast, other SST modes such as Indian Ocean Dipole (IOD),

Pacific Decadal Oscillation (PDO), Tropical Atlantic Variability (TAV) and Atlantic Multidecadal Oscillation (AMO). An accurate ocean initialization of UOHC variability in coupled climate models will also play a crucial role in emerging decadal climate prediction efforts.

To monitor, and to quantify uncertainty in the UOHC estimates, a comparison of UOHC in the top 300m using multiple ocean reanalysis products, which include the operational GODAS based on the GFDL MOM.v3 model forced by the NCEP Reanalysis 2 (R2) surface fluxes (GODAS_MOM3), its control simulation (MOM3_CTL), the experimental GODAS that is identical to the GODAS_MOM3 except the GFDL MOM.v4 was used (GODAS_MOM4), and the National Oceanographic Data Center (NODC) objective ocean reanalysis based on in situ observations only, was made. During the next phase of the project, we plan to implement monitoring of various UOHC products supported by the OCO.

3.1.3. Monitoring of the Atlantic Meridional Overturning Circulation (AMOC) based on the GODAS: The Atlantic Meridional Overturning Circulation (AMOC) has been selected as one of the metrics for the CLIVAR Ocean Synthesis Evaluation Project. To assess the feasibility of an ocean data assimilation system, i.e., the GODAS, we conducted an analysis of GODAS ability in simulating AMOC variability, as well as its sensitivity to data assimilation schemes. We estimated AMOC using (a) the operational GODAS that assimilates temperature down to 750m, (b) the deep ocean GODAS, identical to the operational GODAS except it assimilates temperature down to 2200m, and (c) the Argo GODAS which assimilates the Argo salinity in addition to in situ temperature above 750m. The low frequency variability of AMOC simulated by the operational GODAS is similar to that in observations, and has potential to be used as a real time monitoring tool for AMOC.

3.1.4: Maintenance and improvement of the GODAS website and Monthly Ocean Briefings: As the CPC has access to the operational oceanic and atmospheric reanalysis data and the seasonal climate outlooks made by the NCEP's Climate Forecast System (CFS), CPC is well positioned to provide the user community with a timely and accurate assessment and interpretation of the evolution of the state of the global ocean, its interaction with the atmosphere, and its prediction by CFS. The information about the current state of the ocean continued to be disseminated via the CPC's GODAS website: http://www.cpc.ncep.noaa.gov/products/GODAS/

Dissemination of the ocean state information via the website is continued to be augmented through an operational product referred to as "Monthly Ocean Briefing" (MOB) that was first implemented in May 2007. The MOB is based on conference call and a PowerPoint presentation, and is held around the 6th day of each month. The schedule of MOB is sent by email to a growing distribution list that contains both internal and external colleagues. The distribution list and conference call are open to anyone who is interested in the ocean briefing. The ocean briefing has been regularly attended by internal and external participants, and through interactions with the user community, the content of the PPT presentation has improved with time.

The ocean briefing PPT, made available on the web site, is widely used by a broad user community. The averaged monthly hits on the current month PPT has increased from 692 in

2008 to 1482 in 2009 (Fig. 2). The hits reached 2776 in August 2009 because our discussions on the recent TAO buoy damage and its potential impacts on monitoring and forecasting the emerging 2009/2010 El Nino brought intense interests from both researchers and news media (Fig. 2). More on this event will be discussed further in Section 4 on "Education and Outreach."

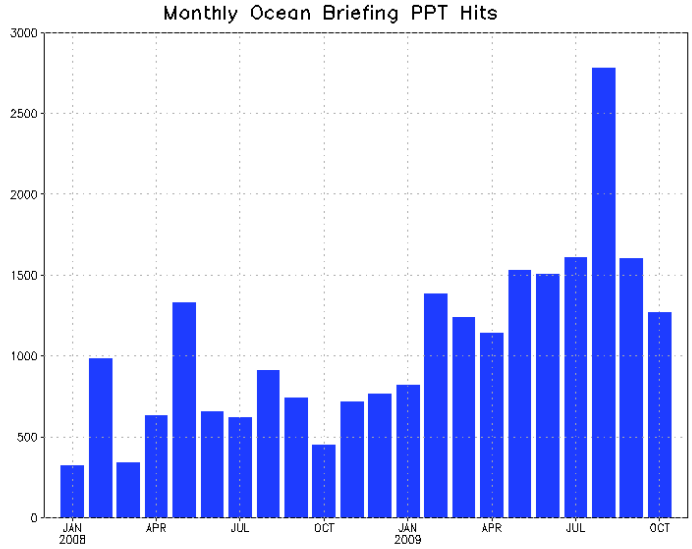

Fig. 2. The accumulative hits within a month on the current "Monthly Ocean Briefing" PPT for January 2008 – October 2009.

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

This particular sub-task was initiated in the middle of the FY09. The eventual goal of the task would be to maintain an ocean data assimilation capability that could be used for Observing System Experiments (OSEs). The urgency of this capability was highlighted by the failure the two eastern most lines of the TAO array in 2009 just at the time when a warm ENSO system was developing. Failure of the TAO data led to a wide range of speculations, and questions, about the impact of missing data on the real-time ENSO forecasts (Lubick 2009).

As part of this task we have acquired the Global Ocean Data Assimilation System (GODAS) run operationally at the NCEP. We have made some preliminary runs and assessment of the GODAS MOM4 for 1990-2005. Fig. 3 illustrates a baseline assimilation experiment that is completed as part of this project, and compares the assimilation against the operational GODAS. Small differences in the operational GODAS, and the simulation completed by us provides with confidence that assimilation system is running correctly.

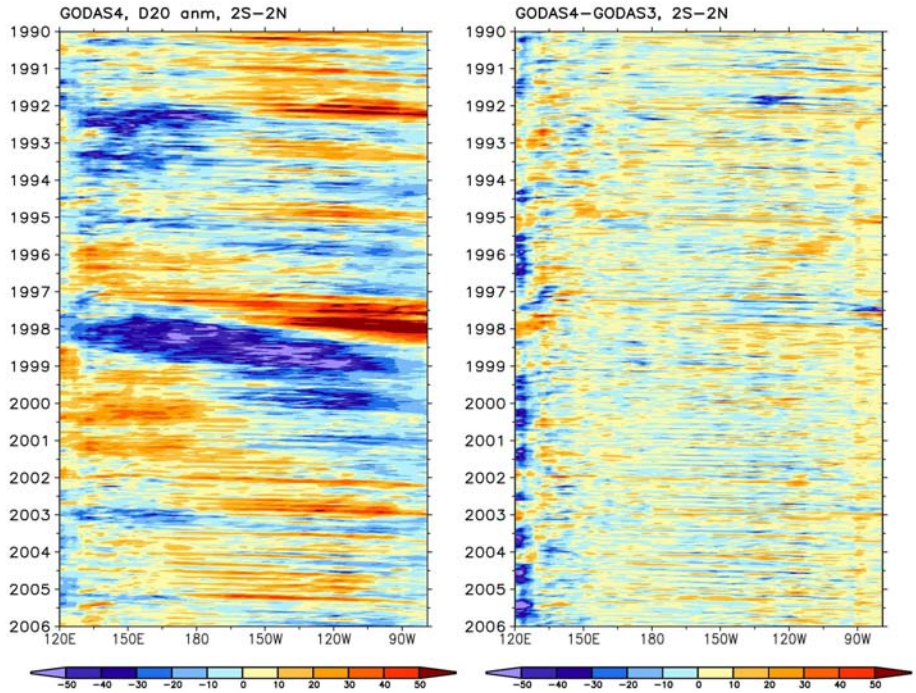

Fig.3. The depth of 20 degree isotherm anomaly (meter) for GODAS MOM4 (left) and GODAS MOM4 minus GODAS MOM3 (operational GODAS) in 2S-2N.

The ocean data assimilation system is now being prepared to make the TAO data Observing System Experiment where TAO data will be withheld to investigate sensitivity of the quality of the GODAS ocean analysis to TAO data.

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

3.3.1. Development of CMORPH High-Resolution Global Precipitation Analyses: Over the past year, we have succeeded in creating a prototype system to generate global oceanic precipitation analyses with further improved quantitative accuracy and consistency for extended applications of this data set in monitoring and examinations of air-sea fresh water fluxes. Specifically: *We extended the CMORPH precipitation analyses back to February 2000 using the current algorithm.* The construction of the 10-year high-resolution global precipitation record would enable us a variety of applications such as the investigation of air-sea fresh water exchanges and their relation to salinity variations at various temporal and spatial scales and the examinations of the intensity changes in heavy precipitation events in association with climate variations and changes; *We developed a prototype system for real-time processing of CMORPH with improved quantitative accuracy and long-term consistency.* Preliminary tests showed significant improvements of the Kalman Filter-based CMORPH (Fig. 4). The present version CMORPH is generated on a real-time basis. The high-resolution precipitation is available to general public through ftp from NOAA/CPC (ftp.cpc.noaa.gov/precip).

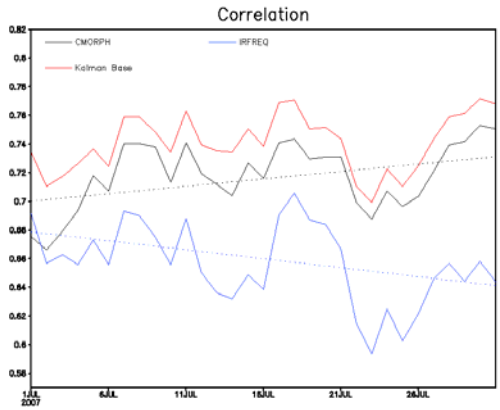

Fig. 4: Time series of correlation between radar-estimated precipitation and satellite precipitation estimates derived from a) IR observations (blue); b) the original CMORPH (black); and c) the prototype Kalman Filter (KF) CMORPH over CONUS.

<u>3.3.2: Development of "CPC Merged Analysis of Precipitation (CMAP)" global precipitation analysis:</u> This component of our project involved two foci: routine updates of the CMAP data sets, and the examinations of the best strategy for removing bias in the oceanic precipitation analyses. Following which *we updated the monthly and pentad CMAP precipitation analyses and used it for quantitative assessments and real-time monitoring of global oceanic precipitation.* 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 October, 2009, the monthly CMAP data set is available for a 30-year period from January 1979 to October 2008. The pentad analysis is available from January 1979 to August 2009; *We examined the best strategy for removing the bias in the satellite estimates of oceanic precipitation*. In FY2009, we developed a new technique to correct the bias in the satellite estimates through matching the probability distribution of satellite estimates with that of the in situ measurements. We performed a series of experiments to examine how the availability and spatial distribution of the in situ measurements may impact the effectiveness of the bias correction for the satellite precipitation estimates over the global oceans. Preliminary results showed that precipitation bias can be removed substantially over most of the tropical oceans with existing network of moored buoys while in situ measurements from additional locations (~250 globally) are desirable to reduce the uncertainty in the magnitude of oceanic precipitation over extra-tropical regions (Fig. 5).

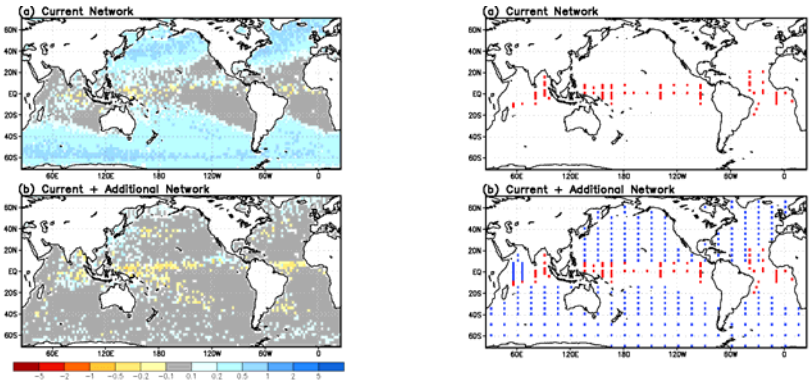

Fig. 5: Simulation results of the remaining biases (mm/day, left column) in the satellite estimates of oceanic precipitation after correction is made by comparison with two sets of networks of in situ measurements (right panels). The results with the existing (red dots) and additional (blue dots) are plotted in upper and bottom panels, respectively. Monthly CMAP precipitation analyses from 1979 to 2008 are assumed to be the 'truth'. Satellite estimates and in situ measurements are synthesized by adding biases and random error of various magnitudes to the 'truth'. Bias correction is then performed for the 'satellite estimates' through PDF matching and the bias corrected 'satellite estimates' are compared to the 'truth' to asses the impact of the in situ network to the effectiveness of the bias correction.

3.3.3: Comparison of P-E with changes in surface salinity: In FY2009, we continued our efforts to examine the oceanic fresh water flux (P-E) as depicted in the observed data sets and the NCEP operational reanalyses. One limitation of using the existing observed data sets in quantitative assessments of fresh water fluxes is the bias in the oceanic precipitation and evaporation. To reduce the uncertainty, multiple sets of published data sets are utilized in the examination. The precipitation data sets used include the monthly precipitation fields CMAP, GPCP, and the TRMM, while the evaporation data sets include those of OAFlux, GSSTF Version2, HOAPS Version 3, and J-OFURO Version2.

Mean and standard deviation of the individual estimates are utilized as the 'best guess' and the proxy index of the uncertainty of the precipitation / evaporation fields, respectively. Oceanic precipitation / evaporation averaged over the global oceans from 60°S-75°N is 3.00 / 3.71 mm/day, with an estimated uncertainty of 0.14 / 0.30 mm/day. Fig. 6 presents the latitudinal profiles of the net fresh water flux (E-P) in the observations and the three sets of NCEP operational reanalyses. The newly developed CFS reanalysis (CFS) shows a slight improvement upon the legend NCEP reanalyses 1 and 2 in the overall magnitude of the oceanic fresh water fluxes. Results described above have been reported at the *OceanObs'09 Conference*. We have also started to examine the relationship between the changes in the fresh water fluxes and those in the salinity.

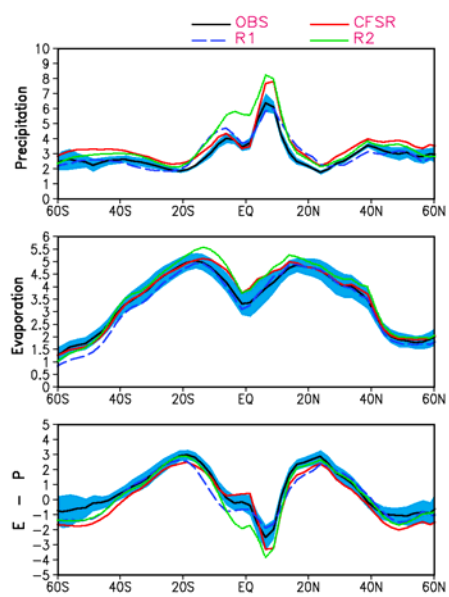

Fig. 6: Latitudinal profile of annual mean zonal mean precipitation (mm/day, upper), evaporation (mm/day, middle), and fresh water flux (mm/day, bottom), as derived from the observations and three sets of NCEP operational reanalyses (R1, R2 and CFSR). The black line indicates arithmetic mean while the blue spread shows the standard deviation among the individual data sets used.

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," 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:

- Our discussions on the recent TAO buoy damage and its potential impacts on monitoring and forecasting the emerging 2009/2010 El Nino brought intense interests from both researchers and news media. Discussions among researchers, managers and journalists have made this issue a top priority for the NOAA officials to resolve;

- Plots in the "Monthly Ocean Briefing" have been used by the NOAA Fisheries Service in the PPT on "The Update on El Nino and the NOAA Response" by Dr. Frank Schwing, Deputy of Southwest Fisheries Science Center;

- Plots in the "Monthly Ocean Briefing" will be used in an extracurricular program that NOAA is piloting in DC public schools to increase marine literacy;

- We have been asked to provide a brief 2009 annual summary on El Nino Southern Oscillation (ENSO), the Pacific Decadal Oscillation (PDO), Productivity (based on the Upwelling Index) and other climatic events/oscillations for the Pacific Coast Ocean Observing System (PaCOOS) Annual Report;

- Plots in the "Monthly Ocean Briefing" have been used by many talks and Community White Papers in the OceanObs09 meeting, which is an important international meeting that reviews the progress in global ocean observation systems, ocean analysis and prediction in the past ten years and makes the future plan for next ten years.

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.

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.

5. Publications and Reports

5.1. Publications by Principal Investigators

Peterson, T.C., and others, 2009: State of the climate in 2008 – Sea surface temperatures, *Bull. Amer. Meteor. Soc*, 90, S47-S49.

Huang, B., Y. Xue, X. Zhang, A. Kumar, and M. J. McPhaden, 2009: The NCEP GODAS ocean analysis of the tropical Pacific mixed layer heat budget on seasonal to interannual time scales. *J. Climate*, conditionally accepted.

Huang, B., Y. Xue, A. Kumar, and D. Behringer, 2009: Low-frequency AMOC Variability: An Assessment based on an Ocean Data Assimilation System, *Geophys. Res. Lett*., submitted.

Huang, B., Y. Xue, and D. Behringer, 2008: Impacts of Argo salinity in NCEP Global Ocean Data Assimilation System: The tropical Indian Ocean. *J. Geophys. Res.*, 113, doi:10.1029/2007JC004388.

Xue, Y., Alves, O., Balmaseda, M., Ferry, N., Good, S., Ishikawa, I., Lee, T., McPhaden, M., Peterson, D., & Rienecker, M., 2010: Ocean state estimation for global ocean monitoring: ENSO and beyond ENSO. In Proc. *"OceanObs'09: Sustained Ocean Observations and Information for Society"* Conference (Vol. 2), Venice, Italy, 21-25 September 2009, Hall, J., Harrison D.E. and Stammer, D., Eds., ESA Publication WPP-306.

Balmaseda, M. & Co-Authors, 2010: Role of the ocean observing system in an end-to-end seasonal forecasting system. In Proceedings of *OceanObs'09: Sustained Ocean Observations and Information for Society* (Vol. 2), Venice, Italy, 21-25 September 2009, Hall, J., Harrison, D.E. & Stammer, D., Eds., ESA Publication WPP-306.

Trenberth, K.E. & Co-Authors, 2010: Atmospheric reanalyses: A major resource for ocean product development and modeling. In Proceedings of *OceanObs'09: Sustained Ocean Observations and Information for Society* (Vol. 2), Venice, Italy, 21-25 September 2009, Hall, J., Harrison, D.E. & Stammer, D., Eds., ESA Publication WPP-306.

Lee, T. & Co-Authors, 2010: Ocean state estimation for climate research. In Proceedings of *OceanObs'09: Sustained Ocean Observations and Information for Society* (Vol. 2), Venice, Italy, 21-25 September 2009, Hall, J., Harrison, D.E. & Stammer, D., Eds., ESA Publication WPP-306.

Stammer, D. & Co-Authors, 2010: Ocean information provided through ensemble ocean syntheses. In Proceedings of *OceanObs'09: Sustained Ocean Observations and Information for Society* (Vol. 2), Venice, Italy, 21-25 September 2009, Hall, J., Harrison, D.E. & Stammer, D., Eds., ESA Publication WPP-306.

Joyce, R., and P. Xie, 2008: Updates to Retrospective Reprocessing and Kalman Filter CMORPH. The 4th International Precipitation Working Group Meeting, Beijing, CHINA, October 13 – 17, 2008.

Joyce, R., and P. Xie, 2009: A Kalman Filter Approach to Blend Various Satellite Rainfall Estimates in CMORPH (Invited), GSMaP International Symposium, Tokyo, JAPAN, Febuary 16-18, 2009.

Xie, P., S. Yoo, R. Joyce, and Y. Yarosh, 2009: Precipitation analysis for improved monitoring of global climate. 34th Annual Climate Diagnostics and Prediction Workshop, Monterey, CA, Octoner 26 – 30, 2009.

Xie, P., and S. Yoo, 2009: Uncertainties in the Global Oceanic Precipitation Observed by the Current Generation Merged Satellite Products. OceanObs'09, Venice, Italy, September 21 – 25, 2009.

Stockdale, T., and Co-authors: Understanding and predicting seasonal to interannual climate variability – the producer perspective. White paper for the World Climate Conference -3, September 2009.

5.2. Other Relevant Publications

Balmaseda, M. & Co-Authors, 2010: Role of the ocean observing system in an end-to-end seasonal forecasting system. In Proceedings of *OceanObs'09: Sustained Ocean Observations and Information for Society* (Vol. 2), Venice, Italy, 21-25 September 2009, Hall, J., Harrison, D.E. & Stammer, D., Eds., ESA Publication WPP-306.

Lubick, N., 2009: Bouy damage blurs El Niño forecasts. *Nature*, 461, 455.