Progress Report

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

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Budget Summary
FY 2022: $270,068

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1. Project Summary

Ocean plays an important role in influencing global climate variability. The ocean's influence on the atmosphere extends from weather to climate on sub-seasonal, seasonal, decadal and centennial timescales, and includes diverse phenomena of societal consequence such as weather and climate extremes, droughts, and floods. Due to their large thermal inertia, and coverage of ~70% of the surface of the globe, ocean monitoring is also a key in understanding and anticipating the potential influence of human induced change in the Earth System and is the place where such influences are first detected with confidence.

Given the importance of ocean climate variability, the fundamental deliverable 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) make informed decisions either to mitigate or to take advantage of the influences resulting from the evolving ocean climate conditions, (b) provide enabling datasets to the science community to improve our understanding of ocean climate variability, and (c) keep a pulse on slowly evolving changes in the ocean conditions. The importance of this project originates from the fact that raw ocean observations do not provide a synthesis view of its state, and a methodology for converting individual observations into a form that could be easily analyzed is required for an effective ocean climate information and service delivery system.

This project is a partnership between the Office of Global Ocean Monitoring and Observing (GOMO) and the Climate Prediction Center (CPC) and focuses on the development, maintenance, and dissemination of real-time ocean monitoring products to the user community.

The products disseminated as part of this project rely critically on the ocean observing system supported by the GOMO and provide a synthesis of the state of the global oceans, together with real-time monitoring of ocean climate variability on different timescales. The outcomes of the project are crucial for an end-to-end delivery of an ocean climate information system that connects gathering of the ocean observations to the dissemination of readily usable ocean products to the 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 delivery of ocean monitoring and forecast products to the operational and research community:

The Global Ocean Data Assimilation System (GODAS) website, hosted by the CPC, serves a global user community with real-time ocean monitoring and ocean prediction products. The website also provides access to the GODAS data sets that can be used for (a) improved understanding of ocean climate variability, and (b) validating data from different in situ ocean observing systems. Under this sub-task, specific work items and products delivered in FY23 are highlighted below.

2.1.1. Maintain the GODAS website and respond to user's requests:

We continued to maintain the ocean monitoring website to disseminate real-time ocean climate information to the user community. Components of ongoing activities under this task included:

- Routine maintenance of the ocean product delivery website.
- Providing responses to the user queries in a timely manner.

2.1.2. Maintain Monthly Ocean Briefing:

Utilizing real-time ocean products at CPC, we continued to provide the "Monthly Ocean Briefing". These briefings include a summary of the observed climate anomalies in different ocean basins and forecasts for various modes of coupled variability. The slide deck for monthly briefing is distributed to the community via a listserv (with ~ 600 subscribers) and is also delivered via a conference call around the 8^{th}-12^{th} of each month. On occasions, the standard set of briefing material is supplemented by detailed discussion of current climate anomalies of societal importance. For example, in FY23 we included discussions of the prolonged marine heat waves in the southern Gulf of Mexico/Caribbean and their impact on corals and marine ecosystems near Florida; relative importance of record-breaking warming in the North Atlantic vs. El Nino teleconnection on the 2023 Atlantic seasonal hurricane activities, among others.

2.1.3. Maintain "Annual Ocean Review" and contribute to the heat flux, SST and ENSO sections in the BAMS Annual Climate Report:

In February 2023, we provided the "Annual Ocean Review" summarizing the major features of the state of global oceans in 2022. We also led the ocean heat flux section and contributed to the sea surface temperature and ENSO sections in the Ocean Chapter of the 2022 BAMS Annual Climate Report.

2.1.4 Maintain SST analysis monitoring and investigate impact of NSST bias on real-time CFSv2 ENSO forecasts.

SST analyses have been widely used for weather and climate forecasting and monitoring. However, on occasions, significant differences exist among SST products resulting from differences in the input data sources, analysis procedures and other factors. This creates challenges for interpreting climate monitoring and prediction products. In order to deliver uncertainty/consistency quantification among SST analyses in a timely manner, we continue to maintain a website to monitor multiple SST analysis. The website provides real-time SST intercomparisons from five SST data sets which are archived as part of CPC operational monitoring efforts. The products are used to support various operational products, such as ENSO monitoring, seasonal hurricane outlook etc. The utility of the SST comparison is highlighted from the following example. Recently users reported that CFSv2 displayed an unusual cold bias at 0-month-lead Nino34 forecasts with early October 2023 initial conditions. This feature was not found in other NMME models. We also found that CFSR exhibited a cold bias (~0.3C) in the eastern equatorial Pacific Ocean since July 2023 (Fig. 1c). The CFSR bias had a clear footprint immediately in the 0-month-lead CFSv2 SST forecast. The cold initial condition bias rapidly grew via positive feedback in the coupled system, leading to >0.6 C cold bias at 0-month-lead forecast (Fig. 1d). NSST has similar bias pattern as CFSR (Fig. 1b). Because NSST is used to provide SST nudging source of CFSR system, it suggested that cold bias in NSST played an important role for cold bias in CFSv2 short-lead forecasts from September to November initial conditions.

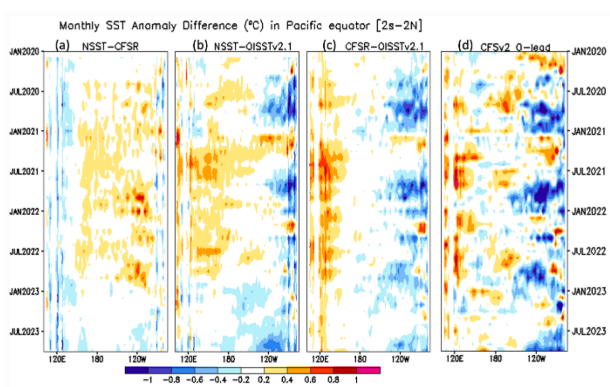

Figure 1: Longitude-time diagrams of (a) NSST minus CFSR, (b) NSST minus OISSTv2.1, (c) CFSR minus OISSTv2.1, and (d) 0-month lead CFSv2 SST anomaly bias at the equator during 2020-2023. Unit in °C.

.2.1.5 Development of a framework for real-time comparison of in situ ocean observations with reanalysis products.

In situ ocean observations are used intensively to support operational weather and climate prediction, data assimilation in real time, and for research and development activities like model validation and improvement, and model-based reanalysis. However, details about the usage of ocean observations in the real-time operational analysis remain unclear to the observational community. On the other hand, model developers in the operational centers have little knowledge of the fidelity of operational ocean analyses data in real time. In other words, there is a longstanding disconnect between the investments in ocean observations and their utilization in model-based analysis and prediction systems. Towards bridging the gap between the observation and modeling communities, we collaborated with NOAA PMEL researchers to develop a capability for the real-time comparison of in situ ocean observations with operational analysis products. Specifically, our objectives were:

(1) Validate model-based reanalysis against in situ observations.
(2) Assess model biases in real-time and quantify their statistics over time.
(3) Utilizes assembled databases to investigate questions of scientific relevance to enhance our understanding and predicting ocean variability.

In FY23, we successfully set up procedures to update the observational and model database in real-time. Three observational datasets are archived, including Global Telecommunication System's (GTS) data stream used at NCEP for operational ocean data assimilation system (hereafter referred to as NCO); the United States Navy Fleet Numerical Meteorology and Oceanography Center (FNMOC); and global fixed moorings maintained by Pacific Marine Environment Laboratory (PMEL). For the model-based analysis, CFSR was chosen because (1) CFSR is used to provide atmosphere & oceanic initial conditions for the current NCEP operational seasonal forecast system (CFSv2), and (2) hourly model output allow direct comparison with high resolution mooring data.

We focused on developing procedures to visualize model-buoy comparison in the tropical Pacific basin. The comparisons focused on surface flux related meteorological variables. We developed spatial comparison and time series comparison at individual mooring sites. Figure 2 (upper panel) shows the weekly spatial distribution of mean bias of wind speed between CFSR and TAO moored arrays. It shows the CFSR surface winds were weaker than PMEL data in the western-central Pacific during 05-12, October 2023. Figure 2 (bottom panel) provides more details of comparison at a specific buoy site (140ºW,0ºN). It shows that NCO data (red line) is very close to PMEL data (blue dots). CFSR surface winds were weaker than the two observed data set. This is consistent with the spatial comparison shown in Fig. 2a. We are currently working on developing a new web interface to disseminate real-time information to the community.

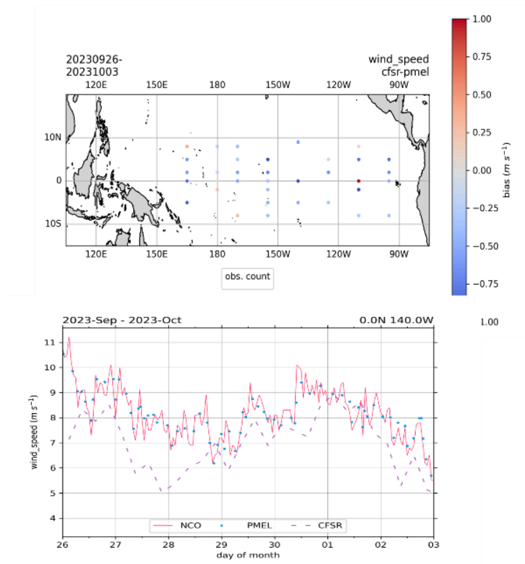

Figure 2: (upper panel) Surface wind speed difference between CFSR and PMEL data at TAO moored array during September 26 to October 3, 2023, (bottom panel) time series of surface wind speed from NCO (red line), PMEL (blue dot) and CFSR (purple dashed) data sets.

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2.1.6 Evaluation of global ocean model simulations with UFS MOM6

Global ocean model driven by prescribed atmosphere forcings provides a framework for evaluating, understanding, and improving ocean component of coupled model. Such OMIP-type simulations allow us (1) to investigate ocean physical mechanisms that force climate variability in real time, (2) to assess relative contribution of atmospheric forcings vs. ocean initial conditions on climate event, and (3) to evaluate the fidelity of ocean model in the context of supporting NCEP next generation seasonal forecast model and reanalysis system. It is important to develop such a tool to enhance our ocean monitoring capability.

In FY23, we spent considerable effort to configure an OMIP type simulation using the ocean sea-ice coupled model from the latest Unified Forecast System (UFS). UFS is being developed at NCEP which aims to provide forecasts at sub-seasonal-to-seasonal scales.

We used CPC newly developed conventional only atmospheric reanalysis (CORe) as atmospheric forcing to drive the model. The model was run from 1979 to 2018. Simulations from 1985-2018 were used for model evaluation. We found that the model run has large warm bias

(>1°C) in most of regions (Fig. 3a). A set of experiments with different combination correction terms were next carried out. We found SST mean bias improved by adding radiation, 10m wind and precipitation correction terms together (Fig. 3b). We also found that it is necessary to add weak SSS nudging term to prevent model drift and improve sea surface height (SSH) simulation skill. After adding atmospheric forcing correction term and SSS nudging, the simulation captured observed SST variations very well (correlation coefficient >0.8) in the tropical Pacific, Northeastern Pacific, and northern subtropical Atlantic oceans (Fig.3c). Other variables, such subsurface temperature and SSH variations were simulated reasonably well.

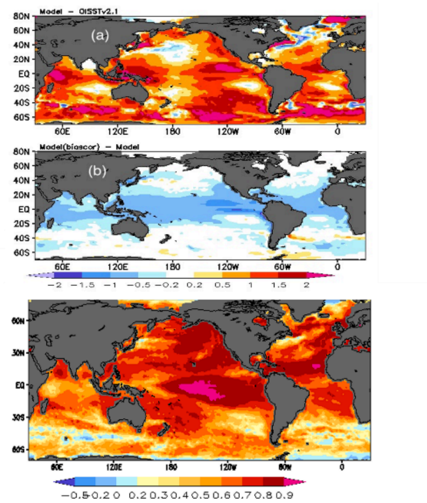

Figure 3: (a) Annual mean bias of model simulation (without bias correction) during 1985-2019 compared with observed SST (NCEI OISSTv2.1). (b) Difference between the simulation run with bias correction and without bias correction. (c) Correlation coefficient between simulated SST anomaly and observation during 1985-2019.

<u>Deliverables</u>:

- Provide real-time ocean climate information, for example, SST, ocean heat content, air-sea exchanges of heat, momentum and fresh water, sea level, to a global uer community.
- Provide an expert assessment of the state of global oceans monthly via "Monthly Ocean Briefings."
- As needed, provide ENSO updates during the monthly TPOS Working Group calls.

2.2. *Sub-Task 2: Real-time Ocean Reanalyses Inter-comparison Project (ORA-IP) in support of assessing the influence of in situ ocean observations.*

Ocean reanalysis (ORA) and seasonal prediction systems are now operational at several centers. Skill for seasonal prediction of surface temperature and precipitation over the US depends critically on the skillful prediction of SST anomalies associated with ENSO, and towards that, Tropical Pacific Observing System (TPOS) is a critical observing system. To document the influence of TAO moorings and its temporal variation on the ocean analysis, CPC initiated the Real-time Ocean Reanalysis Intercomparison Project (Real-time ORA-IP) to quantify uncertainties in ORAs from various operational centers. CPC successfully built an archive of ocean reanalyses from nine operational seasonal prediction centers. This archive includes historical monthly ocean temperature analysis, and its real-time updates. A web-based real-time ocean monitoring system to compare ocean anomalies from multiple analyses, as well as a quantification of their uncertainty, has been put in place for 1981-2010 climatology and for 1993-2013 climatology.

Maintenance of ORA-IP project requires following ongoing tasks that were part of FY23 work plan layout:

- Continuously updating archived databases as assimilation systems at operational centers are updated. In FY23, we have replaced Japan Meteorological Agency's old ocean reanalysis (MOVE-G2)) by its latest system MOVE-G3 ocean reanalysis.
- Delivered real-time information to the user community with stake in ENSO monitoring and prediction.
- Routinely monitored subsurface ocean conditions in the tropical Atlantic Ocean and global ocean.
- On occasions, side-by-side comparison of ocean analysis indicates that an analysis may be an outlier. In such cases, CPC informs the concerned centers, and often, some issue with the analysis is discovered and subsequently corrected.
- Resolving ad doc issues with data acquisition that at times crop up.

Deliverables:

- Monitor ocean climate variability with ensemble mean of ocean reanalysis products from different operational centers and provide real-time assessment of uncertainties among operational ocean reanalyses.
- Inform operational centers when their ocean analysis consistently deviates considerably from others.

2.3 Sub-Task 3: Global oceanic precipitation and sea surface salinity analyses in support of understanding freshwater budget.

We continued our efforts to update and improve CPC's sea surface salinity (SSS) and precipitation analyses. In particular, we modified our system for improved production stability and refined one of the inputs to CMORPH2 for more frequent sampling (and therefore reduced error) of precipitation over the tropical oceans.

2.3.1. CMORPH Global Oceanic Precipitation Analyses:

During FY2023, we continued our efforts to update the first generation CMORPH (CMORPH1) precipitation estimates and released them routinely to users both inside and outside NOAA for real-time oceanic monitoring as well as climate forecast verifications. Over the global ocean, CMORPH1 is defined by integrated raw satellite estimates against the GPCP version 2 merged analysis of global monthly precipitation analysis, achieving a homogeneous long-term climate record of high-resolution (8km x 8km / 30-minute) starting from January 1998 and updated on a real-time basis (4 hours latency). Fig. 4 illustrates an example of total precipitation and precipitation anomalies for December 2023 observed by CMORPH1. Precipitation anomaly pattern associated with the ongoing ENSO event is clearly observed.

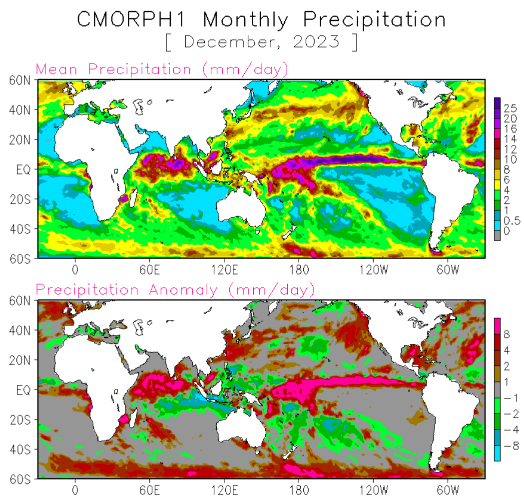

Figure 4: Monthly precipitation (mm/day, top) and precipitation anomaly (mm/day, bottom) for December, 2023 as estimated by the operational first generation CMORPH (CMORPH1) integrated satellite product.

In FY23, we also worked on the second generation CMORPH (CMORPH2). CMORPH2 will replace CMORPH1 once the real-time production becomes more stable, and the historical record is constructed for the past 30 years (effort supported by different projects). Specifically, during FY2023, we built a mirror system of the CMORPH2 real-time production at a local workstation so that missing analyses caused by unstable IT environment and issues in the input data sets may be recovered quickly. We also refined the algorithm to generate one of the inputs to the CMORPH2, the Geostationary Precipitation Estimates (GPE). GPE plays an important role in defining precipitation estimates over the Tropical Ocean where passive microwave (PMW) based retrievals have poor spatial sampling. Strong precipitation is well observed over the tropical oceans, across the Pacific and the Indian oceans.

We have established a procedure to quantitatively examine the CMORPH satellite precipitation estimates on a quasi-routine basis using the precipitation measurements from the TAO, PIRATA, and RAMA. While uncertainties exist in the buoy measurements, comparisons of satellite estimates of precipitation against the buoy measurements, which are the ONLY direct measurement of oceanic precipitation, provide important insights on the quality of satellite estimates over open oceans. Table 1 displays the comparison statistics of the CMORPH2 against the buoy measured daily precipitation over tropical ocean for a 5-year period from 2018 to 2022, while Fig. 5 shows a comparison of time series of monthly precipitation. This comparison can be done only in a delayed mode due to the availability of the buoy data.

Table 1: Comparison Statistics of the CMORPH2 Daily Precipitation against Buoy Measurements for 2018 and 2022

	Statistics	TAO/TRITION (Pacific)	RAMA (Indian)	PIRATA (Atlantic)	All
CMORPH2	Correlation	0.70	0.60	0.65	0.63
	Bias (%)	29.0	25.1	8.9	21.5

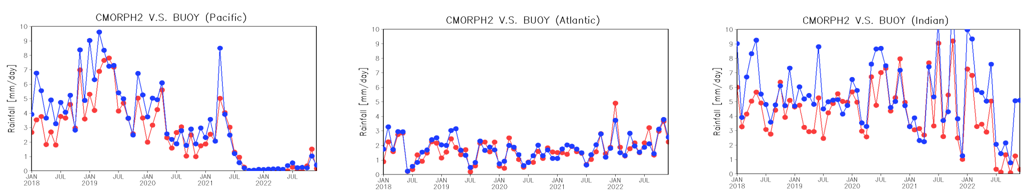

Figure 5: Time series of monthly mean precipitation (mm) averaged from buoy measurements (red) and bias corrected CMORPH2 (blue) at all moored buoy locations over the tropical Pacific (top), tropical Indian Ocean (middle), and tropical Atlantic (bottom).

2.3.2. BASS In-situ – satellite blended analysis of global SSS:

During FY2023, we continued routine production of the in situ – satellite blended analyses of pentad and monthly SSS analyses over the global ocean (BASS). The pentad BASS analysis is updated automatically every day for a rolling 5-day period ending the day before. The monthly analysis is processed manually during the first week of a month, with all inputs preprocessed and quality controlled. The outputs of the grid analyses are uploaded to the CPC ftp site for public release.

2.3.3. Diagnostic study of SSS - fresh water flux:

We continued our efforts to generate packages of global SSS and freshwater flux and provide them to the CPC Ocean Briefing. The package comprises of in situ – satellite blended SSS analysis described in section 2.3.2, precipitation from CMORPH1 satellite estimates and oceanic evaporation defined by adjusting CFSR analysis against observations. The packages contain graphic display as well as brief discussions of SSS and freshwater variations (anomalies and tendencies) over the global ocean.

Fig. 6 provides an example of the monthly anomaly maps of sea surface salinity (SSS), freshwater flux (E-P), precipitation (P), and evaporation (E) for December 2023, as a part of the monthly SSS / freshwater budget monitoring package for the month. Anomalies of SSS exhibit a very clear response to those of the freshwater flux (especially the precipitation) over the tropical ocean. The Hovermöller diagram (Fig. 7) shows a rapid change in SSS anomalies from saltier to freshened over the equatorial central and western Pacific from late 2023, attributable to the freshwater flux forcing anomalies associated with the ongoing ENSO.

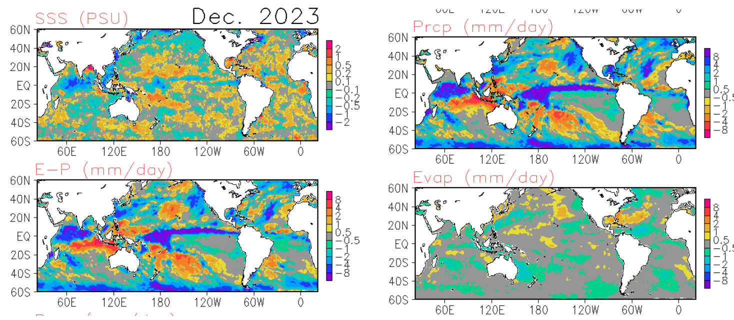

Figure 6: Monthly anomalies of Sea surface salinity (SSS, upper), freshwater flux (E-P, 2nd from top), precipitation (3rd from top), and evaporation (bottom) tendency for December 2022, constructed using the data described in the sections 2.3.1.and 2.3.2.

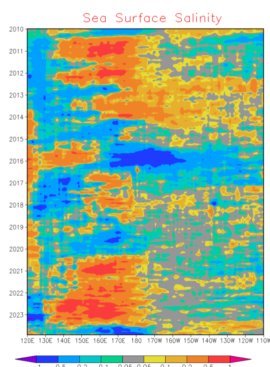

Figure 7: Hovermöller diagram of monthly Sea Surface Salinity (SSS) defined by the NOAA Blended Analysis of Sea-surface Salinity (BASS) over the equatorial (5ºN-5ºS) Pacific.

3. Outreach and Education

3.1.   Ocean products

We served a broad user community for our global ocean monitoring products. The plots from Monthly Ocean Briefing PowerPoint and the GODAS web site are routinely used at CPC in support of ENSO prediction, hurricane prediction and temperature and precipitation outlooks. They are also routinely used by NWS offices and other operational centers around the world. The briefing material is also widely used as research materials by researchers in peer reviewed publications and teaching materials for graduate and college students by the academy.

The Real-time Ocean Reanalysis Intercomparison Project allows us to have a regular communication with the operational climate prediction centers around the world (ECMWF, JMA, BOM, MET, MERCATOR, GFDL, NASA). The communication includes topics on real time data delivery delay, any apparent errors in data, and any new upgrades of operational ocean analyses that need to be included in the intercomparison project.

The research works supported by this project has been reported in various peer reviewed journals, conferences, and workshops.

3.2 Precipitation and Salinity 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 CMORPH high-resolution satellite precipitation data have been cited more than 3,000 times. CMORPH satellite precipitation data sets are available publicly through ftp from CPC server (ftp.cpc,ncep.noaa.gov/precip/CMORPH_V1.0).

The NOAA Blended Analysis of Surface salinity (BASS) has been constructed, as part of this project, for an eleven-year period from January 2010 and is updated on a real-time basis. A paper describing the monthly BASS has a citation index of more than 50. The monthly and pentad BASS salinity analyses are routinely utilized by CPC Ocean Briefing for the monitoring of global ocean. The BASS data sets are also released publicly through ftp (ftp.cpc.ncep.noaa.gov/precip/BASS).

4. Publications and Reports

4.1. Publications by Principal Investigators

- **Wen, C**., P.W. Stackhouse, J. Garg, **P. Xie**, L. Zhang, M. Cronin (2023) Global Ocean Heat, Freshwater, and Momentum Fluxes [in “state of the Climate in 2022”], Bull. Amer.Meteor. Soc. , 104 (9), S168-172, https://doi.org/10.1175/BAMS-D-23-0076.2.
- Kim, D., Lee, SK., Lopez, H. Foltz, GR., ***Wen, C***., West, R. & Dunion, J. (2023). Increase in Cape Verde hurricanes during Atlantic Niño. *Nature Communications* 14, 3704. https://doi.org/10.1038/s41467-023-39467-5

4.2 Presentations:

- **Wen, C**. (2022): Real-time Ocean Reanalyses Intercomparison Project, SynObs Kick-off and OS-Eval/CP-TT workshop (invited)

5. Data and Publication Sharing

All dataset developed that are either developed under this project or are used to support products are available to the users via open access. Relevant datasets can be obtained from following access points:

Ocean data, products and Monthly Ocean Briefings:
https://www.cpc.ncep.noaa.gov/products/GODAS/

Multi-SST intercomparison:
https://origin.cpc.ncep.noaa.gov/products/GODAS/multiSST_body.html

Real-time Ocean Reanalyses Intercomparison Project:
https://www.cpc.ncep.noaa.gov/products/GODAS/multiora_body.html

Indian Ocean Monitoring and Forecasting
https://www.cpc.ncep.noaa.gov/products/international/ocean_monitoring/indian/IO_monitoring_fcsts/io_index.shtml

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

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

6. Project Highlight Slides

Provided.