Comparative Analysis of Upper Ocean Heat Content Variability from Ensemble Operational Ocean Analyses

Yan Xue[1], *Magdalena A. Balmaseda*[2], *Tim Boyer*[3], *Nicolas Ferry*[4], *Simon Good*[5], *Ichiro Ishikawa*[6], *Michele Rienecker*[7], *Tony Rosati*[8], *Yonghong Yin*[9], *Arun Kumar*[1]

[1]*NOAA/NCEP*, [2]*ECMWF*, [3]*NOAA/ NESDIS/NODC*, [4]*Mercator-Océan*, [5]*Met Office Hadley Centre*, [6]*Japan Meteorological Agency*, [7]*NASA/GSFC/GMAO*, [8]*NOAA/GFDL*, [9]*Centre for Australian Weather and Climate Research (CAWCR)*

Upper ocean heat content (HC) is one of the key indicators of climate variability on many time-scales extending from seasonal to interannual to long-term climate trends. For example, HC in the tropical Pacific provides information on thermocline anomalies that is critical for the long-lead forecast skill of ENSO. Since HC variability is also associated with SST variability, a better understanding and monitoring of HC variability can help us understand and forecast SST variability associated with ENSO and other 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 HC anomalies in coupled climate models could also contribute to skill in decadal climate prediction.

Errors, and/or uncertainties, in the estimation of HC variability can be affected by many factors including uncertainties in surface forcings, ocean model biases, and deficiencies in data assimilation schemes. Changes in observing systems can also leave an imprint on the estimated variability. The availability of multiple operational ocean analyses (ORA) that are routinely produced by operational and research centers around the world provides an opportunity to assess uncertainties in HC analyses, to help identify gaps in observing systems as they impact the quality of ORAs and therefore climate model forecasts. A comparison of ORAs also gives an opportunity to identify deficiencies in data assimilation schemes, and can be used as a basis for development of real-time multi-model ensemble HC monitoring products.

The OceanObs09 Conference called for an intercomparison of ORAs and use of ORAs for global ocean monitoring (Xue et al., 2010a). As a follow up, we intercompared HC variations from ten ORAs – two objective analyses based on in-situ data only and eight model analyses based on ocean data assimilation systems. The mean, annual cycle, interannual variability and long-term trend of HC have been analyzed.

Operational ocean analyses

National Centers for Environmental Prediction (NCEP), NOAA/USA

The NCEP produces ORA using the Global Ocean Data Assimilation System (GODAS) (Behringer and Xue, 2004). The GODAS is based on the Geophysical Fluid Dynamics Laboratory's Modular Ocean Model version 3 (MOM3) at 1° with 1/3° equatorial refinement, 40 levels and a 3D variation scheme. Observed temperature and synthetic salinity profiles and observed SST are assimilated daily. A suite of comprehensive global ocean monitoring products has been derived with GODAS (http:// www.cpc.ncep.noaa.gov/products/GODAS). Recently, a new reanalysis for the atmosphere, ocean, sea ice and land over 1979-2009 has been completed as the Climate Forecast System Reanalysis (CFSR). The oceanic component of CFSR includes many advances: (a) the MOM4 ocean model with interactive sea-ice, (b) a 6 hour coupled model forecast as the first guess, (c) inclusion of the mean climatological river runoff, and (d) high spatial (0.5° by 0.5°) and temporal (hourly) model output (Xue et al., 2010b).

Geophysical Fluid Dynamics Laboratory (GFDL), NOAA/USA

The GFDL assimilation system consists of an Ensemble Kalman Filter applied to GFDL's second generation fully coupled climate model CM2.1, (Zhang et al., 2007). The ocean component of the ensemble coupled data assimilation (ECDA) is configured with 50 vertical levels (22 levels of 10-m thickness each in the top 220 m) and 1° horizontal B-grid resolution, telescoping to 1/3° meridional spacing by 1° near the equator. The atmospheric component has a resolution of 2.5° x 2° with 25 vertical levels. The system is fully coupled, assimilating both atmosphere and ocean observations contemporaneously building covariances between the component models fluxes. Observed temperature and salinity profiles and SST are assimilated daily on the ocean side. The GFDL reanalysis covers the period 1970 to present and is updated monthly (http://www.gfdl.noaa.gov/ocean-data-assimilation).

Global Modeling and Assimilation Office (GMAO), NASA/USA

The GMAO reanalysis uses the GEOS-5 coupled atmosphere-ocean general circulation model which is based on MOM4 (0.5° with 1/4° equatorial refinement and 40 levels) and the GEOS-5 AGCM (1° x 1.25° with 72 levels) model. The atmosphere is constrained by the atmospheric fields from the Modern Era Retrospective Analysis for Research and Applications

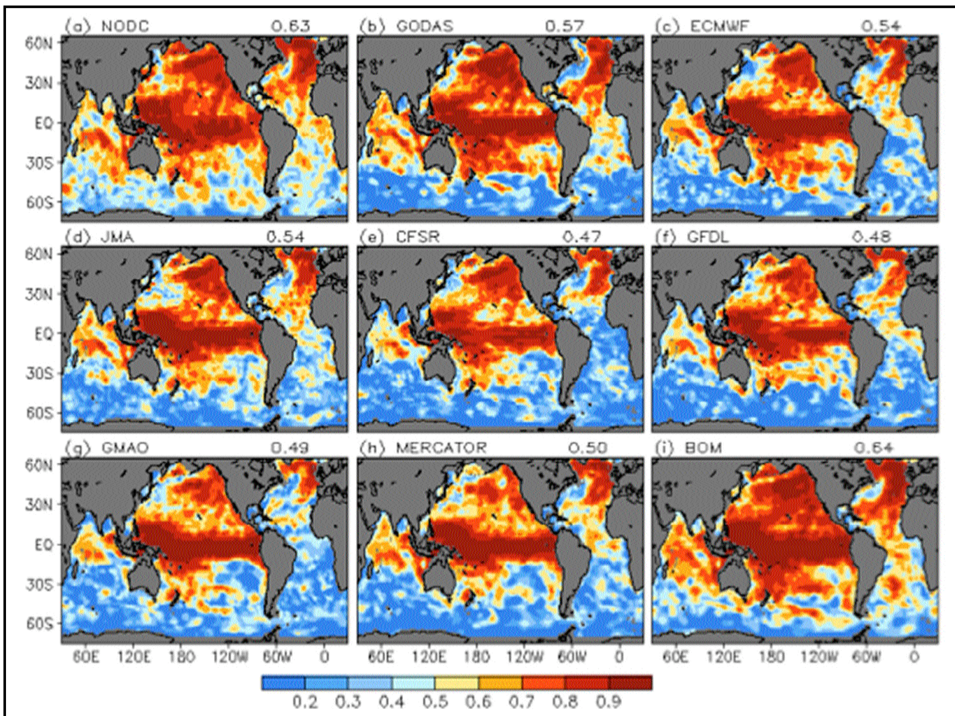

Figure 1. Anomaly correlation with EN3 in 1985-2009 for (a) NODC, (b) GODAS, (c) ECMWF, (d) JMA, (e) CFSR, (f) GFDL, (g) GMAO, (h) MERCATOR, and (i) BOM. The average of correlation over the global ocean is shown on the right top of each figure.

(MERRA) (Rienecker et al., 2011). The ocean data assimilation uses a multivariate ensemble optimal interpolation (EnOI) to infer background-error covariances from a static ensemble of 50 model state-vector EOFs. Observed temperature and salinity profiles and observed SST are assimilated daily. The XBT temperature profiles have been corrected according to Levitus et al., 2009. The climatological sea surface salinity is also assimilated to compensate for errors in fresh water input from precipitation and river runoff.

European Centre for Medium-Range Weather Forecasts (ECMWF)

The ECMWF ocean reanalysis, referred to as ORA-S3, has been operational since August 2006, providing ocean initial conditions for the ECMWF seasonal and monthly forecasts since March 2007. The ORA-S3 is based on the Hamburg Ocean Primitive Equation (HOPE) model (1° with 0.3° equatorial refinement and 29 levels), and 3D Optimal Interpolation (OI) scheme to assimilate temperature, salinity, altimeter derived sea-level anomalies and global sea level trends ((Balmaseda et al., 2008). A selection of historical and real-time ocean analysis products can be seen at http://www.ecmwf.int/products/forecasts/d/charts/ocean.

Mercator-Ocean, France

The Mercator-Ocean reanalysis, referred to as PSY2G2, covers the 1979-present time period and is used at Météo-France for coupled seasonal forecasts. The PSY2G2 is based on the OPA8.2 ocean model in the ORCA2 global configuration at 2° with 0.5° equatorial refinement and 31 levels. In situ temperature and salinity profiles, SST maps and along track SLA data are assimilated weekly using a fixed basis reduced order Kalman filter with the SEEK formulation (Drévillon et al., 2008).

Japan Meteorology Agency (JMA)

The JMA reanalysis, referred to as MOVE/MRI.COM-G (Usui et al. 2006), was implemented in March 2008. The analysis system covers the quasi-global ocean (75°S-75°N) with 1° grids with 0.3° equatorial refinement and 50 levels. It provides pentad and monthly fields from 1979 to present (http://ds.data.jma.go.jp/tcc/tcc/products/clisys/index.html).

Bureau of Meteorology (BOM), Australia

The BOM reanalysis, called PEODAS (POAMA Ensemble Ocean Data Assimilation System, http://poama.bom.gov.au/research/assim/index.htm, has been developed for the period from 1980 to present. It is an approximate form of ensemble Kalman filter system (Yin et al. 2010). Both in situ temperature and salinity observations are assimilated, and current corrections are generated based on the ensemble covariances.

Met Office, United Kingdom

The UK Met Office delivers an objective monthly temperature analysis based on in situ observations with 1° grid and 42 levels (EN3_v2a, Ingleby and Huddleston, 2007). A historical reanalysis for the period 1950 to present is available, and the real time updates have approximately one month lag (http://www.metoffice.gov.uk/hadobs/en3).

National Oceanographic Data Center (NODC), NOAA/USA

The NODC delivers an objective seasonal temperature analysis based on in situ observations. The analysis is at 1° grid and 16 levels ranging from the ocean surface to 700 m in depth from 1955 to 2009 (Levitus et al., 2009).

Comparison of upper ocean heat content

Upper ocean heat content is defined as the average temperature in the upper 300m (hereafter, HC300). HC300 anomalies (HC300a) are derived by removing the 1985-2009 climatology in each data set. Since the EN3 is based on in situ data only with monthly resolution, it is used to as the baseline to compare the other ORAs. The temporal correlation with EN3 is generally high (> 0.8) in the tropical Pacific, North Pacific and North Atlantic (Figure 1). The correlation is poor near the western boundary currents, the Gulf Stream and Kuroshio Extension, which is probably because there are insufficient data to constrain

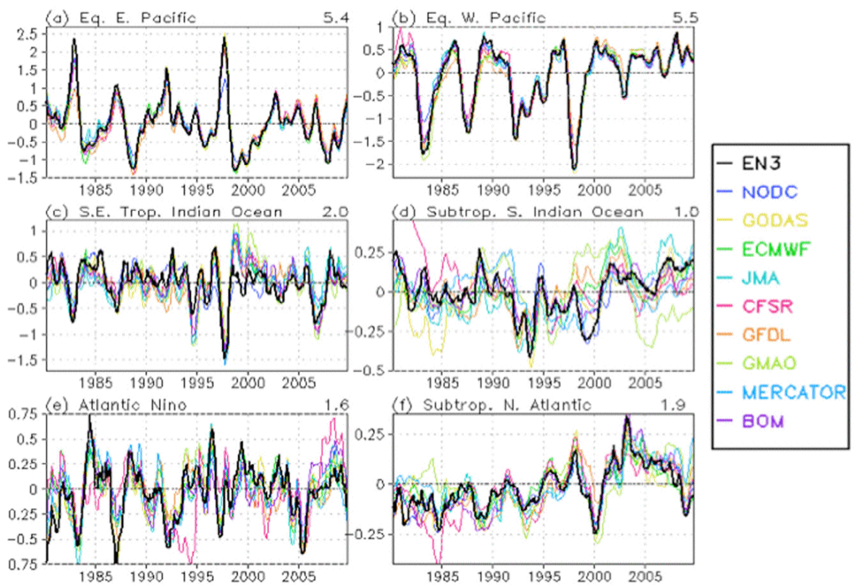

Figure 2. Time series of 7-month running means of HC300a (°C) averaged in (a) the equatorial eastern Pacific (150W-90W, 5S-5N), (b) equatorial western Pacific (130E-170W, 5S-5N), (c) southeast tropical Indian Ocean (90E-110E, 10S-0), (d) subtropical South Indian Ocean (45E-110E, 30S-15S), (e) Atlantic Niño defined as HC300a differences between the region of (20W-20E,1S-0) and (60W-20W,0-10N), and (f) subtropical North Atlantic (80W-10W, 15N-30N). The signal to noise ratio is shown on the right top of each figure.

EN3 in those areas. It is interesting that the correlation is moderately high in the tropical Indian Ocean, and has a pattern resembling the IOD pattern. The correlation is relatively low in the tropical Atlantic, and mid- to high-latitude southern oceans where observations are sparse.

Since analyzed HC300a provides information important for seasonal forecast skill of ENSO, IOD, and tropical Atlantic Niño, a set of HC300a indices characterizing those tropical SST variabilities are intercompared (Fig. 2). The signal to noise ratio (SNR), calculated as the ratio of standard deviation of the ensemble mean and ensemble spread, of HC300a indices is high (~5.4) in the equatorial eastern and western Pacific. The variability of HC300a has a decadal shift: variability is much weaker and the equatorial western Pacific is much warmer after 2000 than before 2000 (Figure 2a-b). We also note that the warming during the 1982/83 (1997/98) El Niño is significantly underestimated by the GFDL (NODC) (Figure 2a). Large negative HC300 anomalies in the southeast tropical Indian Ocean associated with the IOD events in 1982, 1994, 1997 and 2006 were well captured by model-based analyses. (Figure 2c). However, the NODC and EN3, without the benefit of surface forcing to compensate for sparse observations, missed the positive anomaly in 1999 (Figure 2c). The SNRs in the subtropical South Indian Ocean, subtropical North Atlantic and Atlantic Niño are much lower than that for ENSO and IOD (Figure 2d-f). Note that the HC300a in the subtropical South Indian Ocean and subtropical North Atlantic have an upward trend from 1993 to 2009, which is shown in the linear trend map in Figure 3.

The multi-model ensemble trend of HC300 is calculated for 1993-2009 (Fig. 3a) and can be compared with the trend in altimetric sea surface height (Xue et al., 2010b). There are large regions of the ocean where the SNR is low, indicating a large uncertainty in the trend. These are generally areas where the correlation with EN3 is low across many of the ORAs. The SNR is also low in the eastern Equatorial Pacific where the ensemble mean trend is also very low. All ORAs show an increasing (decreasing) HC300 in the western tropical Pacific (subtropical eastern Pacific). The increasing HC300 in the central North Pacific, and a decrease south of Alaska and off the west coast of North America simulated by all ORAs, is consistent with an overall downward trend in the PDO index. The increasing HC300 in the subpolar North Atlantic consistent in all ORAs is related to the weakening of the subpolar gyre since 1995. The increasing trends in the subtropical South Indian Ocean and subtropical North Atlantic are weak, but are consistently simulated by all ORAs.

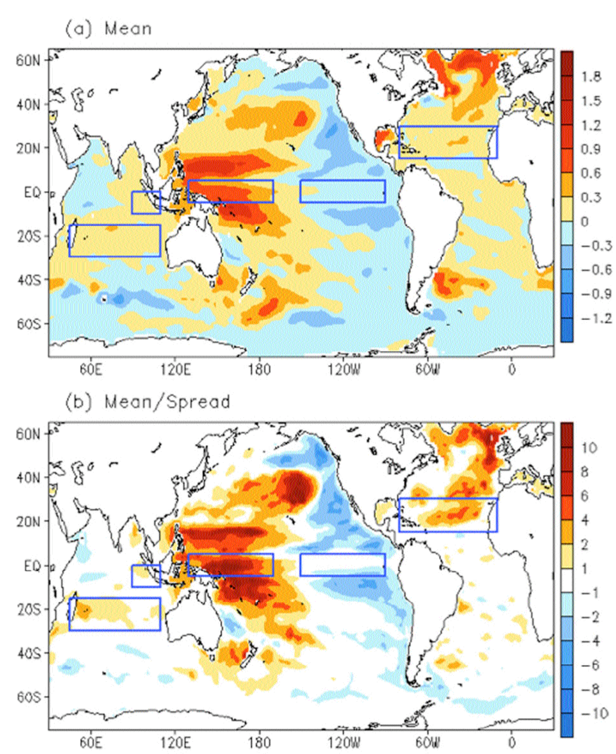

Figure 3. Linear trends of HC300a based on 10 ORAs in 1993–2009 (°C/decade). (a) Ensemble mean, (b) ratio between ensemble mean and ensemble spread. The boxes show the regions used for the time series of the average HC300a in Figure 2.

Summary

Our analysis demonstrates that the current generation of ORAs is promising in providing reliable estimation of global HC300 variability to the extent that they can be used in understanding and monitoring climate signals in HC300. This activity could be extended to routine exchange of ORAs, and implementation of real-time multi-model ensemble HC300 indices in the near future.

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U.S. CLIVAR Director, David Legler, Moves on...

Following a decade of successful leadership at the helm of the U.S. CLIVAR Office, Dr. David Legler assumed his new position as Director of NOAA's Office of Climate Observations within the NOAA Climate Program Office in January 2011. We wish to acknowledge here some of the many contributions by David to stimulate planning and to promote implementation of U.S. CLIVAR science. Beginning in 2001, David established new mechanisms to facilitate communication with the national and international research community including the U.S. CLIVAR website and the *VARIATIONS* newsletter providing updates on evolving program planning, exciting research findings, new funding opportunities, and a calendar of events. Over the years, he worked closely with the Scientific Steering Committee, Panels and Working Groups to identify and scope new research thrusts and with the Interagency Group of NASA, NOAA and NSF managers (and more recently engaging DOE and ONR) to coordinate interagency sponsorship of:

- Field Campaigns to collect high-resolution observational datasets to improve process understanding and address model biases, including EPIC, SALLJEX, NAME, AMMA, DIMES, VOCALS and the upcoming DYNAMO;
- Climate Process Teams to link observational and process-oriented research to modeling for the purpose of addressing key uncertainties in climate models;
- Climate Model Evaluation Projects to increase diagnostic research into the quality of model simulations, leading to more robust evaluations of model predictions and better quantification of uncertainty in projections of future climate;
- Drought in Coupled Models Projects to expand diagnostic research into the physical mechanisms of drought and to evaluate its simulation by climate models;
- Limited lifetime working groups focused on salinity, the Madden Julian Oscillation, western boundary currents, high latitude surface fluxes, drought, decadal predictability, and most recently two new groups on hurricanes and Greenland ice sheet/ocean interactions; and
- Workshops and scientific meetings to foster community engagement on specific research topics, including ocean observing system requirements and integrated Earth system analyses.

Much of U.S. CLIVAR progress can be traced directly to David's skill in soliciting community input to guide climate research directions and fostering commitments by participating funding agencies to ensure their implementation. He departs leaving a strong legacy. The U.S. CLIVAR Scientific Steering Committee, Interagency Group, and Project Office look forward to working with David in his new role and wish him continued success.