Ocean Data Assimilation Research at GFDL

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1. Project Summary

Estimating the state of the Earth System is critical for monitoring our planet's climate and for predicting changes to it on time scales from months to decades. Toward these ends, the vast number of atmospheric observations and the growing number of ocean observations must be combined with model estimates of the state of the Earth System by means of data assimilation systems. This project explores the development of new data assimilation techniques using state-of-the-art coupled climate models and applies these techniques to detecting climate change, improving forecasts on seasonal to interannual time scales while providing estimates of their uncertainty, and improving our understanding of predictability at decadal time scales in order to provide a foundation for the development of a NOAA capability for decadal forecasts. This capability will provide the Nation's decision and policy makers with the best possible climate information on critical problems such abrupt climate change, changes in hurricane activity, drought, and sea-level rise.

The feasibility of seasonal to decadal predictions largely stems from the role the ocean plays in the predictability of slowly evolving modes of variability. The challenge then is to have the capability to represent this low frequency climate variability within our climate models so that initializing them would offer the potential to predict internal variability in addition to externally-forced climate change. Initialization has three main components: the observing system, the assimilation method, and the model. These three components are combined to produce initial conditions for the climate model. One needs to keep in mind that the initialization problem is different from the state estimation problem.

Historically the sub-surface ocean has been very sparsely observed, and some of the data appear to be significantly biased, making the development and testing of ocean initialization schemes difficult. Studies of historical periods are important in order to assess the likely skill of forecasts over a range of different climate states. However, recent and planned improvements to the observational network promise significant improvements in future forecast skill. Perhaps, most important among these is the recent (2003) deployment of a global array of profiling floats by the ARGO program. These provide for the first time contemporaneous measurements of both

temperature and salinity over the upper 2km of the world's oceans, potentially offering a step change in our ability to initialize ocean heat and density anomalies. For example, in the coming decades, can we make useful predictions in the Atlantic Meridional Overturning Circulation? The non-stationary nature of the ocean observing system, particularly due to the paucity of salinity data as well as XBT data only going to 500m, can give rise to spurious decadal variability making it difficult in the assessment of forecasts.

2. Scientific Accomplishments

1. An assessment of oceanic variability for 1960-2010 from the GFDL ensemble coupled data assimilation

The Geophysical Fluid Dynamics Laboratory (GFDL) has developed an Ensemble Coupled Data Assimilation (ECDA) system based on the fully coupled climate model, CM2.1, in order to obtain accurate oceanic initial conditions that are balanced with the climate prediction model. This study provides a comprehensive evaluation for the oceanic variability from the latest version of the ECDA analyzed for 51 years, 1960-2010. Meridional oceanic heat transport, net ocean surface heat flux, wind stress, sea surface height, top 300 m heat content (HC300), tropical temperature, salinity and currents are compared with various in situ observations and reanalyses by employing similar configurations with the assessment of the NCEP's climate forecast system reanalysis (CFSR) (Xue et al. 2010). Results show that the ECDA agrees well with observations in both climatology and variability for 51 years. While systematic model biases are mostly corrected with the coupled data assimilation, some model biases (e.g., strong trade winds, weak westerly winds and warm SST in the southern oceans, T-S biases along the equatorial western Pacific boundary, overestimating the mixed layer depth around the subpolar Atlantic and southern oceans in the winter seasons) are not completed eliminated. For the simulation of the Tropical Atlantic Ocean and global salinity variability, the ECDA shows a good performance compared to existing reanalyses. The ECDA also shows no significant drift in the deep ocean temperature and salinity. In terms of climate variability, the ECDA provides good simulations of the dominant oceanic signals associated with El Nino and Southern Oscillation (ENSO), Indian Ocean Dipole (IOD), Pacific Decadal Oscillation (PDO), and Atlantic Meridional Overturning Circulation (AMOC) during the whole analyzed period, 1960-2010. The ECDA ocean reanalysis from 1960 to present may be found at
http://www.gfdl.noaa.gov/ocean-data-assimilation-model-output.

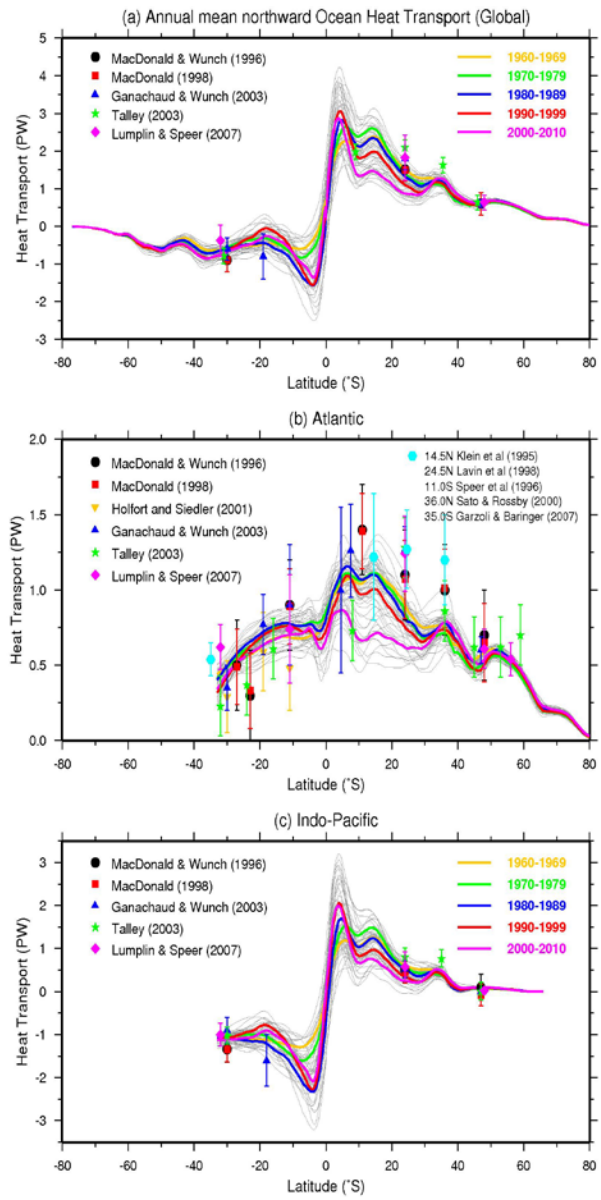

Fig. 1. Comparison of northward oceanic heat transport (unit: PW) from the ECDA (gray lines are annual mean for the individual 51 years (1960-2010), and colored lines denote 10-year mean values) with previously published estimations with error bars (see legend). (a), (b), and (c) represent the global, Atlantic, and Indo-Pacific Oceans, respectively

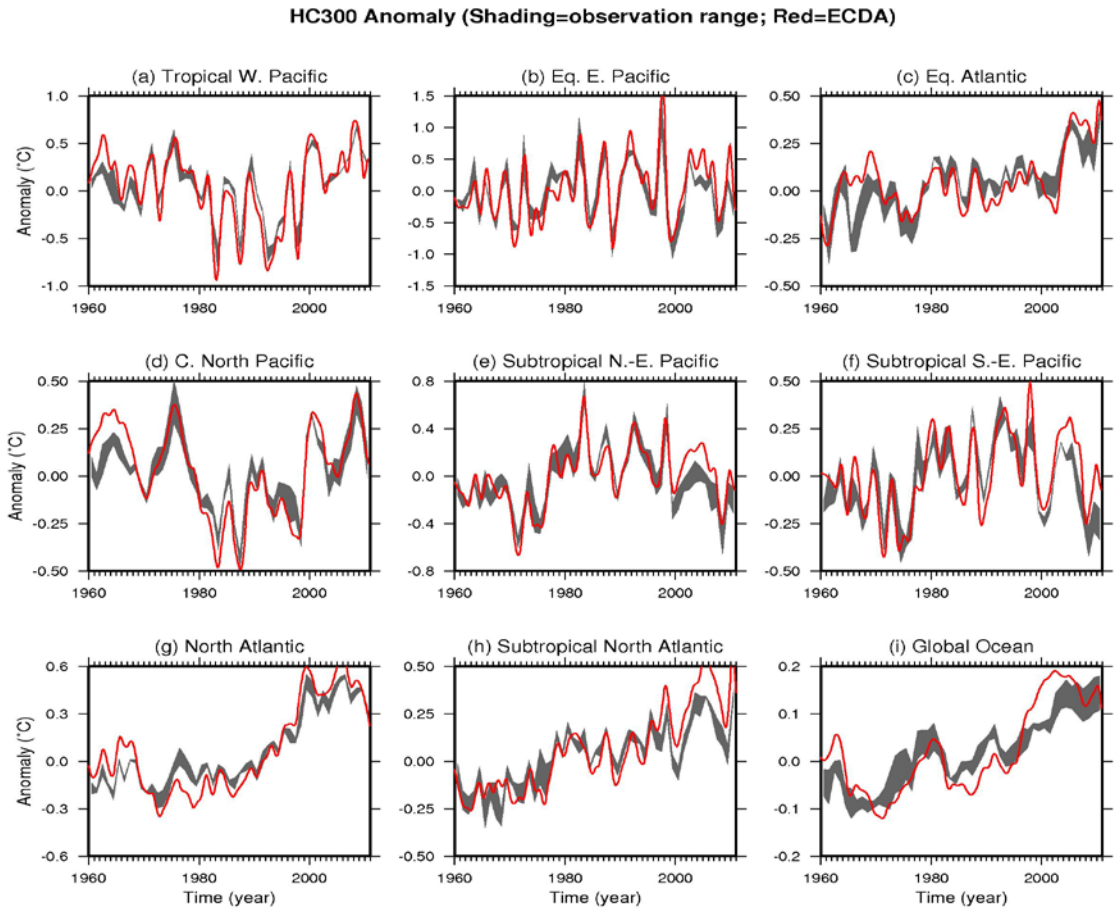

Fig. 2. Time series of 1-year running mean of HC300 anomaly averaged in various boxes for the (red line) ECDA. Shading line indicates the different range among the NODC2009, NODC2005, and EN3 objectively analysis datasets based on only in situ data. Reference period for the anomaly is 1960-2003. (a) Tropical western Pacific (130°E-190°E, 20°S-20°N), (b) equatorial eastern Pacific (210°E-270°E, 5°S-5°N), (c) equatorial Atlantic (310°E-10°E, 10°S-10°N), (d) central North Pacific (180°E-220°E, 20°N-40°N), (e) subtropical northeast Pacific (220°N-270°N, 5°-25°N), (f) subtropical southeast Pacific (220°N-280°N, 5°S-25°N), (g) subpolar North Atlantic (280°E-350°E, 30°N-60°N), (h) subtropical North Atlantic (280°E-360°E, 5°N-25°N), and (i) Global Ocean (0°-360°E, 70°S-70°N)

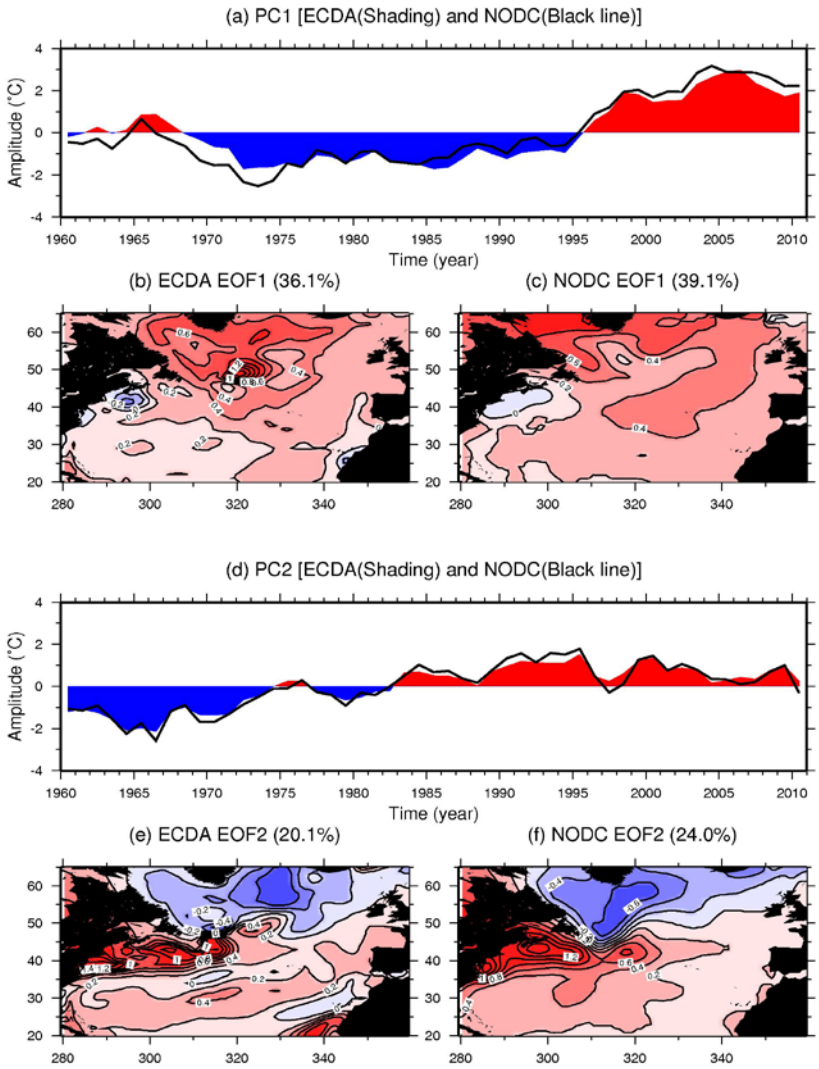

Fig. 3. First two EOFs and PCs of HC300 (°C) anomalies from the ECDA and NODC in the North Atlantic for the period 1960-2010. For the time series, shading (black line) represents the ECDA (NODC). Note that no detrend is applied for the two datasets.

2. NCAR (POPDART-CAMDART) assimilation system:

Over the past few years, NCAR has working toward the long-term goal of establishing a fully-coupled ocean-atmosphere data assimilation system for the Community Climate System Model v.4 (CCSM4). We are developing the capacity to produce ocean and atmosphere state analyses that are suitable for scientific investigation and for initialization of seasonal, interannual and decadal climate forecasting. Ocean initialization is understood to be an integral part of producing skillful long-term climate forecasts, so we pay special attention here to the ocean assimilation system.

Currently, the NCAR assimilation system consists of an Ensemble adjustment Kalman Filter (EaKF) interfacing separately with the atmosphere and ocean components of CESM. Both EaKFs are implemented using the DART algorithm (Anderson et al. 2009) In this configuration,

the Community Atmospheric Model v.4 (CAM4) is used to obtain an 80-member atmospheric analysis, assimilating the same set of raw observations that are used in the NCEP/NCAR reanalysis product. All members of the CAM4 assimilation are boundary forced with the ocean-ice dataset.

Subsurface temperature and salinity data from the World Ocean Database are assimilated daily into the Parallel Ocean Program v.2 nominal 1° global ocean model using a 48-member EaKF. Forcing for each ocean member is obtained from a unique sample of the CAM4 posterior ensemble. In this way, the components of the assimilation are linked through the forcing at the ocean/atmosphere interface. In the ocean EaKF horizontal localization is used to restrict the impact of observations to model state variables in their geographic vicinity. No localization is being applied in the vertical, allowing the observations in the upper regions of the ocean to impact the state at all depths. No explicit variance-inflation is being applied in the filter, so the ensemble spread is being maintained in the ocean largely through forcing by the ensemble of atmospheric states.

Ocean assimilation has been completed over the 8-year period from Jan 1, 1998-Dec 31, 2005. The Argo network of floating temperature and salinity sensors dramatically expanded the observational coverage of the global ocean down to 2000m during this time period, creating an opportunity to better constrain the deeper layers of the ocean.

We use a 48-member ensemble of ocean simulations forced with the identical CAM4 posterior ensembles as s benchmark against which we can demonstrate how assimilation of subsurface data impacts the time/ensemble mean state of the ocean from 2000-2005. Evaluation of the ways in which assimilation alters the time-mean ocean state is ongoing, and here we present only a few examples to demonstrate some of the changes. Fig. 1 shows the Atlantic meridional overturning circulation (AMOC) in the control run ("NoAssim") and the ocean assimilation ("Assim"). Assimilation leads to a stronger AMOC, with more flow below 2500m in the deep western boundary current (DWBC). This is more consistent with estimates from the RAPID array (Fig. 2) and from observational studies of flow in the DWBC (not shown). Assimilation of data also helps reduce systematic temperature biases in the Gulf Stream and Kuroshio Current by improving the pathways of these warm western boundary currents (Fig. 3-4).

Work on improving the ocean assimilation system is ongoing. Plans are in place to move to a fully coupled assimilation system for CCSM4 over the next 2-years, and improving the stand-alone ocean assimilation system is an important preliminary step in that process. Over the next year, we will be focusing on the following aspects of the ocean assimilation system:

1) Understanding the impact that vertical covariance localization has on the analysis and modifying our system accordingly.
2) Refining our observational error estimates to include "representativeness" error. In course resolution models, this can be the dominant observational error source in regions with strong temperature and salinity fronts.
3) Using adaptive ensemble variance inflation to maximize the information we can draw out of the observational network. This will be especially important at ocean depths greater than 1000m, where the boundary-forced ensemble spread is small and where the Argo network is providing new and valuable observational constraints.

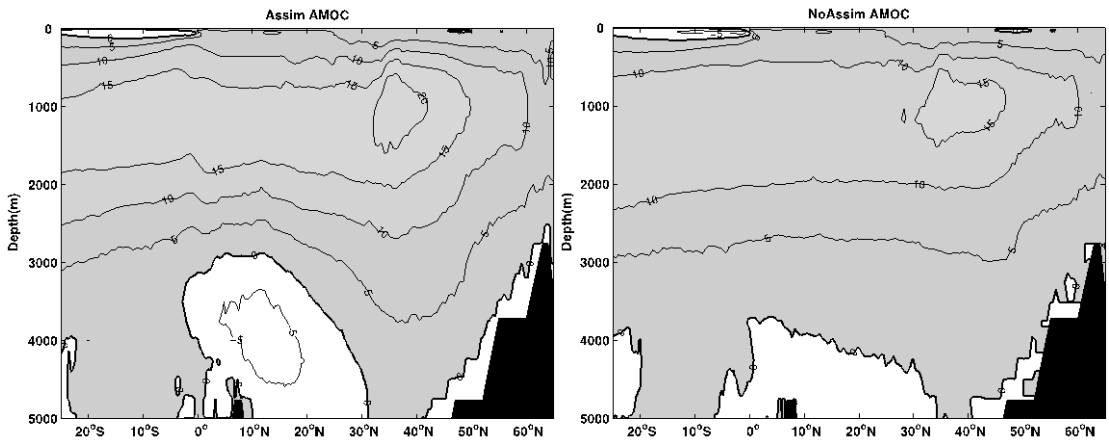

Fig 1. Atlantic meridional overturning circulation (AMOC) averaged over 2000-2005 for Assim (left panel) and NoAssim (right panel). The AMOC is defined as the streamfunction of the net zonal transport in the Atlantic Ocean basin. Each level indicates the depth integrated transport from the surface. Zero contour in bold, contour intervals are 5 Sv (1Sv ≡ 1e6 m3 s−1), shaded areas are positive contours. The maximum value of AMOC in Assim is 22.5Sv (1Sv ≡ 1e6 m3 s−1), and 16Sv in NoAssim.

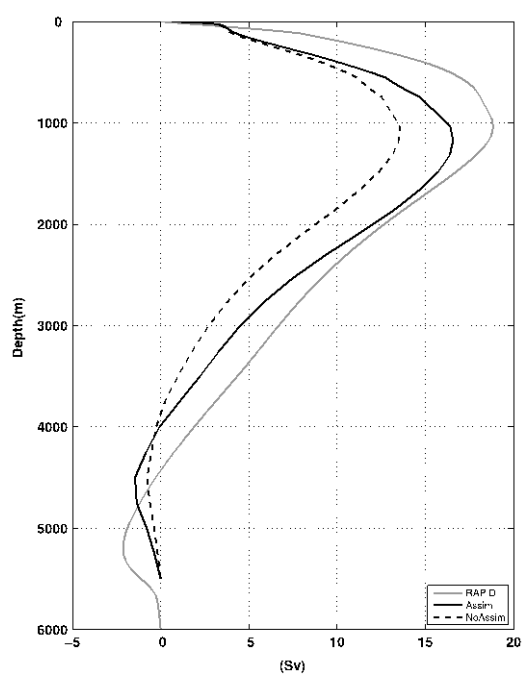

Fig. 2. AMOC profiles at 26oN from Assim (solid line), NoAssim (dashed line) and estimates from RAPID (gray line) for the 21 month overlapping period April 2004 to Dec 2005.

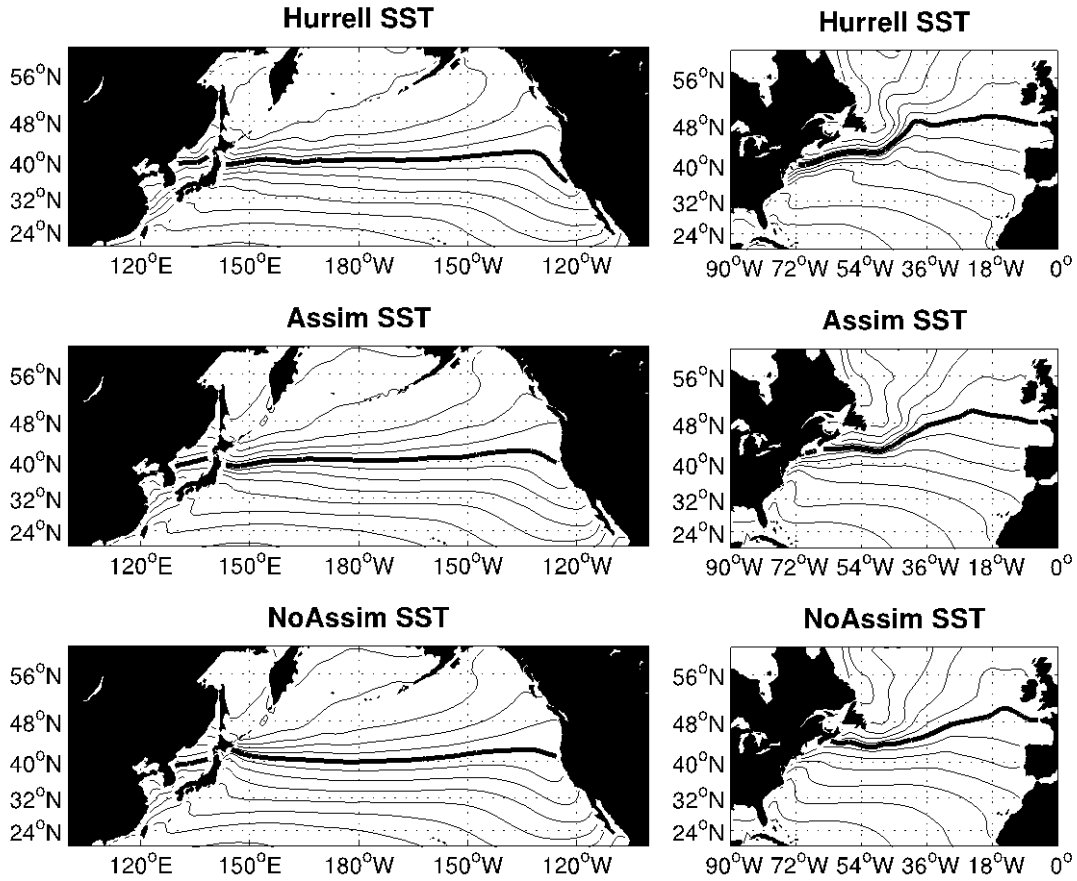

Fig. 3. SST in the subtropical gyres of the Pacific and Atlantic ocean basins from the Hurrell SST dataset (top panel), Assim (middle panels) and NoAssim (bottom panel). Bold line indicates the 14°C isotherm. Contour intervals are 2°C .

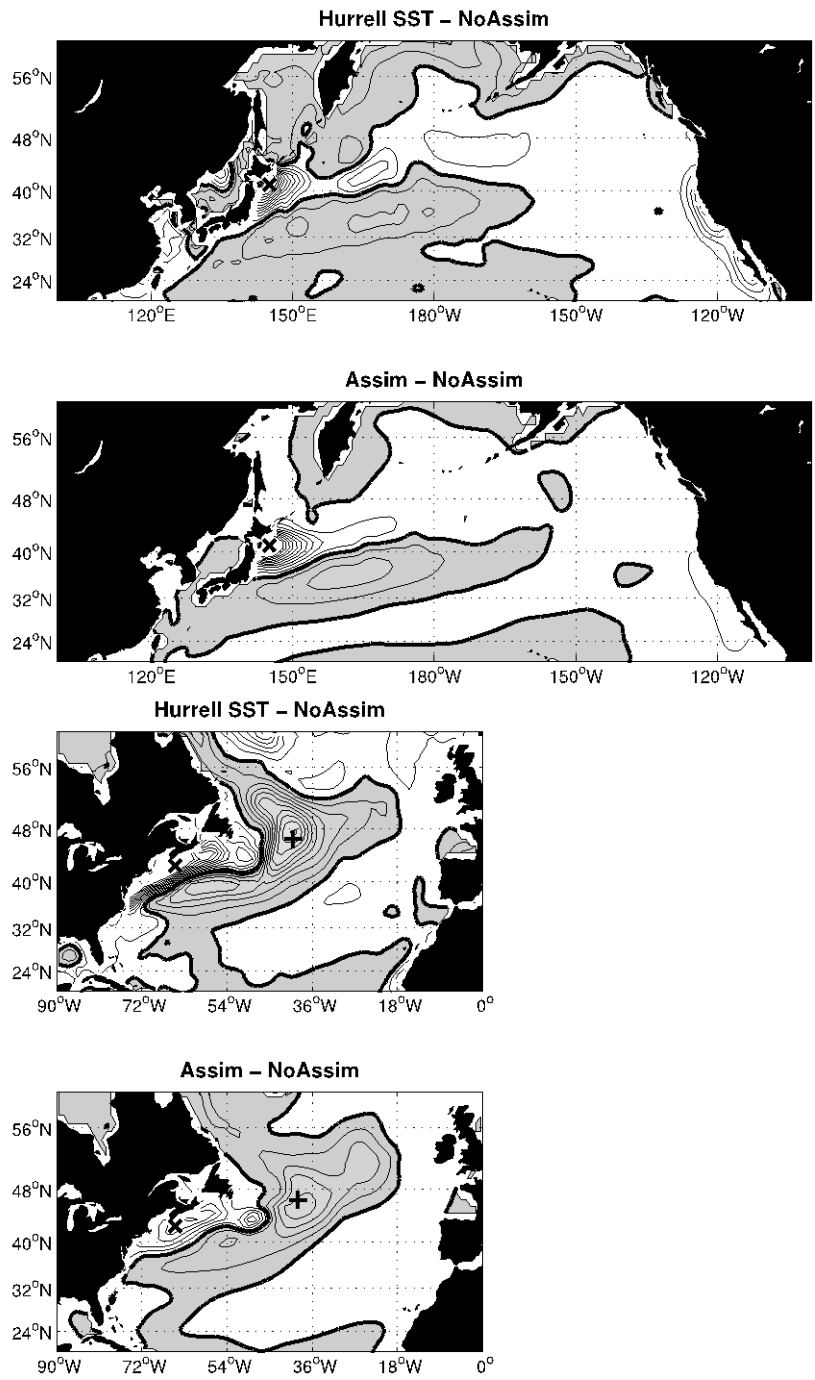

Fig. 4. Difference between the Hurrell SST and the NoAssim SST in the subtropical gyres in the Pacific and Atlantic Ocean basins (top row) and difference between the Assim SST and the NoAssim SST (bottom row). Zero contour indicated in bold, with gray shading over positive contours. Contour intervals are 0.5°C . The“X” in the Pacific at 145°E ,41°N in- dicates a difference of 6°C in top and bottom panels. In the Atlantic, the “X ” at 65°W, 42°N indicates a difference of 6.3°C (top panel) and 2.2°C (bottom panel) and the “+ ” at 39°W, 46°N indicates a difference of 4.3°C (top panel) and 2.1°C (bottom panel).

2.1. Outreach and Education

There is an urgent need for information on how the climate system will change over the next several decades. This is a crucial planning horizon for many aspects of societal infrastructure, including water resource planning and ecosystem management. On decadal time scales and regional spatial scales the climate system is strongly influenced by increasing greenhouse gases and changing aerosols. However, the presence of substantial natural decadal scale variability in the climate system complicates the prediction of decadal scale changes.

A major research activity is underway at GFDL focusing on decadal variability and predictability in the climate system. There are fundamental research challenges in understanding the characteristics and mechanisms of decadal variability, and developing the necessary understanding, observing, assimilation and prediction systems that lead to credible decadal predictions.

It is our vision that GFDL will constitute the research underpinning for the assessment of decadal predictability and the development of a decadal predictions system, and will conduct experimental decadal predictions on an ongoing basis. These experimental decadal predictions will be made available to the wider community, including a National Climate Service and IPCC.

3. Publications and Reports

3.1. Publications by Principal Investigators

Chang, Y., S. Zhang, and A. Rosati (2011), Improvement of salinity representation in an ensemble coupled data assimilation system using pseudo salinity profiles, Geophys. Res. Lett., 38, L13609, doi:10.1029/2011GL048064.

Chang, Y.-S, A. Rosati, and S. Zhang (2011), A construction of pseudo salinity profiles for the global ocean: Method and evaluation, J. Geophys. Res., 116, C02002, doi:10.1029/2010JC006386

S.Zhang, Z.Liu, A.Rosati and T.Delworth (2011),A Study of Enhancive Parameter Correction with Coupled Data Assimilation for Climate Estimation And Prediction Using A Simple Coupled Model" Tellus A 2011,63,10963,DOI:10.3402/tellusa.v63i0.10963

3.2. Other Relevant Publications

The GFDL ocean reanalysis may be found at (http://www.gfdl.noaa.gov/ocean-data-assimilation).