

## **Monsoon Variability in the Arabian Sea from Global 0.08° HYCOM Simulations**

Julie L. McClean  
Climate, Atmospheric Sciences, and Physical Oceanography Division  
Scripps Institution of Oceanography  
University of California San Diego  
Mail Code 0230  
La Jolla, CA 92093-0230  
Phone: (858) 534-3030 Fax: (858) 534-9820 Email: [jmcclean@ucsd.edu](mailto:jmcclean@ucsd.edu)

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### **LONG-TERM GOALS**

The Arabian Sea upper ocean circulation switches direction seasonally due to the change in direction of the prevailing winds associated with the Indian Monsoon. Predictability of the monsoon circulation however is uncertain due to incomplete understanding of the physical processes operating on the monsoon and at other time scales, particularly interannual and intraseasonal. Therefore, the long-term goal of this project is to improve understanding of the physical processes, both regionally and remotely, controlling the variability of the Arabian Sea circulation.

### **OBJECTIVES**

The project objective is to understand how local and remote processes acting on interannual and intraseasonal time scales modify the timing of the monsoon-driven seasonal reversal of the Somali Current (SC) and the Great Whirl (GW) in the Arabian Sea (AS).

### **APPROACH**

Monthly climatological velocity fields constructed from surface drifting buoys (15m) by Beal et al. (2013; their Fig. 3) show that a northward flowing SC, together with the weak anticyclonic flow at 6°N, appear one to two months before the onset of the southwest monsoon. To explore the sequence of events leading up to the early reversal of the western boundary current (WBC) circulation, we are using an existing forced global strongly eddy-active (0.08°) Hybrid Coordinate Ocean model (HYCOM) simulation. This ocean general circulation model (OGCM) is highly realistic and has a hybrid vertical coordinate system. The model simulation was forced with 0.5° Navy Operational Global Atmospheric Prediction (NOGAPS) fluxes for 2003-2012, and was provided to us by A. Wallcraft (NRLSSC). It was initialized from a spun-up climatologically forced HYCOM ocean state, which, in turn was initialized from Generalized Digital Environmental Model 4 (GDEM4) temperature and salinity climatology.

Our project objectives require us to study the interannual variability of the Arabian Sea and northern Indian Ocean hence an OGCM simulation of longer duration is required. Consistent NOGAPS forcing

is only available for 2003-2012, therefore we will carry out a second global  $0.08^\circ$  HYCOM simulation using  $\sim 1.9^\circ$  Coordinated Ocean Reference Experiment II (CORE-II) interannually varying fluxes (IAF) constructed by Large and Yeager (2009). CORE-II fluxes have been evaluated and used broadly in the ocean modeling community (Griffies et al., 2014); currently fields are available for 1948 through 2009, however the time series could be extended in the near future. The simulation will be initialized from the GDEM4 temperature and salinity climatology. The model will be started from rest in 1980 and then spun-up for 12 years; this period will be treated as the model's adjustment period to its initial condition, leaving us with 18 model years to investigate interannual variability and multiple realizations of particular climate mode phases.

Biases in OGCM simulations are due, among others, to limitations in the atmospheric surface forcing. Due to the resource intensive nature of these high-resolution simulations, it is not possible to carry out a consistent suite of sensitivity runs to catalog bias. Comparisons, however, of the two sets of HYCOM output for the overlapping 2003-2009 period should still yield useful information that can help us understand shortcomings in the circulation and water mass properties. Neither simulation is constrained by observations; we choose to first understand how the model physics and forcing depict Arabian Sea variability.

We start our analyses by examining the simulated monthly and daily surface flow fields during the months prior to the monsoon reversal along the western boundary of the Arabian Sea and northern Indian Ocean to determine if the existing HYCOM model reproduces the drifter-based results. The veracity of simulated monthly mixed layer depth (MLD), and temperature and salinity over the upper 2000m of the model water column are assessed using Argo. Altimeter-derived sea surface height anomaly quantities, starting with the amplitude and phase of the seasonal cycle and then focusing on the representation of mesoscale variability, can be compared to HYCOM counterparts.

Remotely generated Rossby waves that propagate westwards across the southern Arabian Sea have been implicated by Beal et al. (2013) as possibly responsible for the pre-monsoon reversal of the SC. To identify significant oceanic remote forcing on the SC due to the arrival of Rossby waves, we will calculate phase/coherence-squared between local sea surface height anomaly (SSHA) and the broader domain for various frequency bands, particularly the interannual (see McClean et al. 2005; their Fig.11). We will also calculate lagged correlations of local variables i.e. SST and SSHA, with local and remote wind stresses and wind stress curl. Our goal is to tease out how the relative contributions of local wind forcing and remote forcing in the form of Rossby waves arriving at the SC, affect the WBC transport variability.

We also seek to understand how the Indian Ocean Dipole (IOD) and the El Niño–Southern Oscillation (ENSO) act to modify the seasonal strength and variability of the WBC circulation as well as that in the broader study region of the Bay of Bengal and the Indian Ocean. As in Prasad and McClean (2004, PM04 hereafter), we will examine changes in sea surface height anomaly (SSHA), thermocline depth, and water mass properties along the Rossby wave propagation path across the southern Arabian Sea during “normal” non-IOD years, strong IOD years, and those years when ENSO impacts the IOD. These analyses will allow us to identify year-to-year differences over the study region as well as model differences that might indicate biases. In the SC time series, we will look for anomalous transport events and then see if there is a relationship to a particular phase of the IOD and/or ENSO. We will then create monthly composites of key variables including surface fluxes for the various phases of the

climate modes to help explain the series of events leading up to the anomalous behavior in the SC, the GW and upwelling strength.

## **WORK COMPLETED**

Modifications to the existing NRLSSC HYCOM set-up are needed to carry out the CORE-II forced simulation. A. Bozec and E. Chassignet (both FSU) modified the HYCOM/CICE code base to use bulk formulae-based CORE-II surface fluxes to force HYCOM/CICE. It is now necessary for us to merge the modified FSU code with the configuration set-up scripts developed by Wallcraft (NRLSSC), which include the capability to interpolate the forcing fields onto the HYCOM grid as part of the model run. FSU and NRLSSC have provided their respective code and scripts, and we are testing the “on the fly” forcing interpolation scripts with a low-resolution counterpart CORE-II HYCOM code. The code is running on Shepard, a Cray XC30, at the Navy DoD Supercomputing Resource Center (Navy DSRC).

Previously, CORE-II HYCOM ingested forcing that was interpolated onto the model grid prior to the model run. The next steps are to set up the 0.08° HYCOM code with the “on the fly forcing” and produce preliminary output. Appropriate parameter inputs will then be evaluated and adjusted for the fine resolution production simulation that will follow.

We have carried out a series of model evaluations of the existing NOGAPS forced 0.08° HYCOM in the Arabian Sea and broader Indian Ocean. We evaluated its realism in the Arabian Sea using Argo estimates of climatological monthly MLD and temperature and salinity over the upper 2000m, altimetry-based sea surface height anomaly statistics, and upper-ocean flow statistics with those from drifting buoys.

## **RESULTS**

Monthly climatological velocity fields at 15 m for 2003-2012 from HYCOM were compared with the monthly climatological fields from surface drifting buoys (15m) constructed by Beal et al. (2013; their Fig. 3). Unlike the drifter fields that show northeastward flow extending along the entire length of the WBC off Somalia in April, HYCOM did not show such flow until May, however the set up of the GW appeared to start in April (Fig.1). Next, we calculated daily geostrophic velocity from the daily model sea surface height for April and May of 2003-2012. Reversals of the SC were found in April during some model years. Now, we need to extract and examine total daily model velocities to better understand the climatological results.

Beal et al. (2013) noted that the appearance of northward flow along the western boundary in April was coincident with the arrival of an annual high in absolute dynamic height, which was attributed to Rossby waves. In Fig. 2, the amplitude and phase of the annual cycles of SSHA from AVISO altimetry and from HYCOM are shown for 2003-2012. The patterns and magnitude of the amplitude of the annual cycle from the observations and the model are generally in good agreement, however we note a phase difference of about 1 month between the model and observations along the Rossby wave propagation path across the southern Arabian Sea.

PM04, from their eddy-permitting OGCM simulation, documented anomalous SSHA behavior in the southern Arabian Sea during the northeast monsoon of a positive IOD year. The anomalous behavior was considered to be due to the suppression of an upwelling Rossby wave producing warmer than

usual temperatures at 100m. Fig. 3 shows time series of potential temperature from HYCOM and Argo data at 100 m averaged over 55°-60°E and 3°-5°N, the region through which the upwelling Rossby wave propagates. As in their study, the observed temperature (in this case Argo) is higher than usual during a positive IOD year i.e. 2007, as the upwelling Rossby wave was not present. HYCOM, however, appears to be biased warm throughout the decade at these depths.

## IMPACT/APPLICATIONS

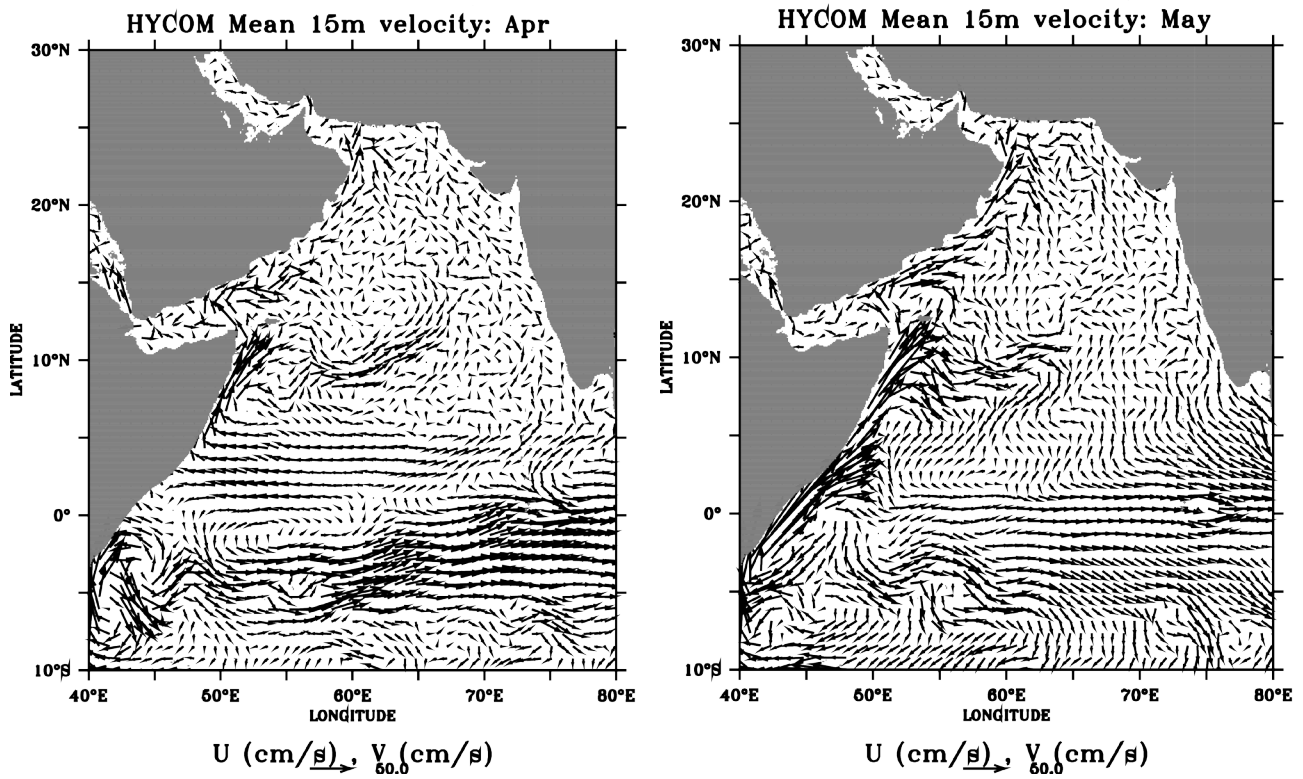
This study will provide a large-scale, long-time period context to explore the dominant processes controlling the upper Arabian Sea circulation that cannot be obtained from observations alone. An assessment of the veracity of the representation of the Arabian Sea circulation in 0.08° HYCOM, as well as an assessment of HYCOM's sensitivity to surface forcing, will be obtained. HYCOM will form the ocean component of the Navy's next-generation fine resolution fully coupled prediction system for seasonal to interannual prediction. In order for coupled prediction to be successful, both the ocean and atmospheric components must show skill in uncoupled mode prior to coupling. Also, improved knowledge of the variability of the upper-ocean circulation of the Arabian Sea is needed to aid surveillance and enhance safety in important shipping lanes in this basin.

## RELATED PROJECTS

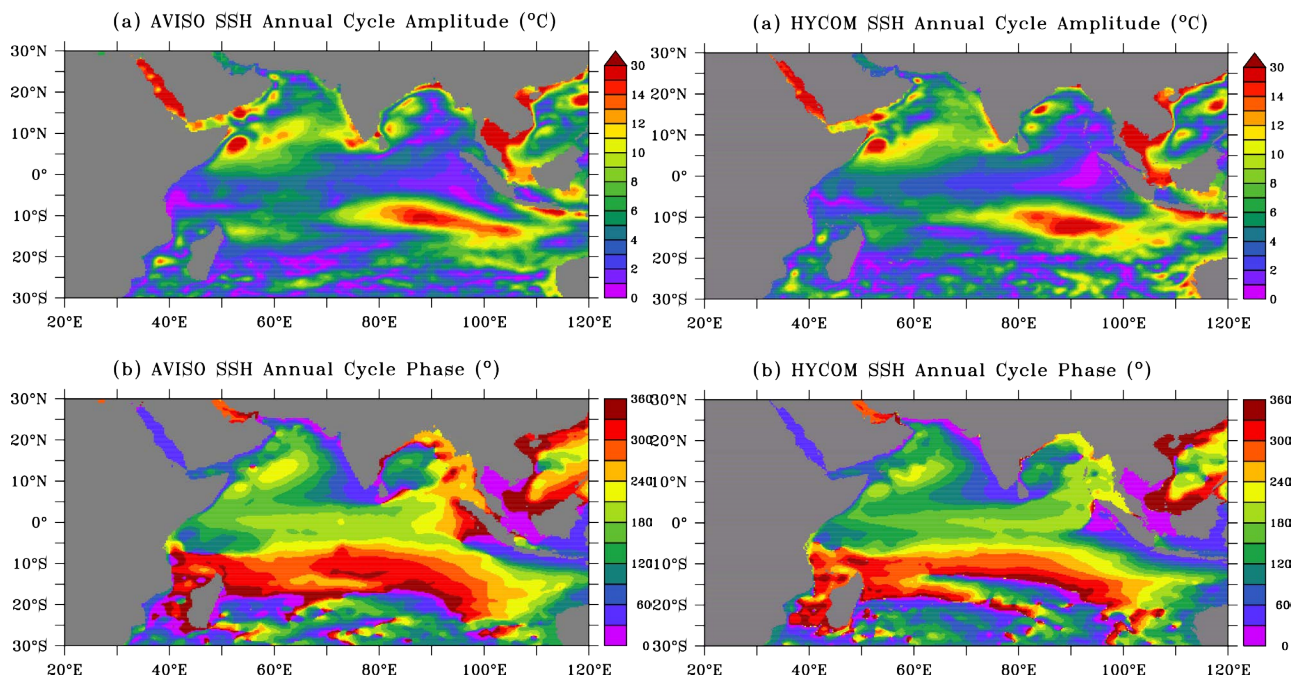
“Optimized Infrastructure for the Earth System Prediction Capability,” Celicia DeLuca (PI). A goal of this project is to incorporate HYCOM into an Earth System Modeling framework.

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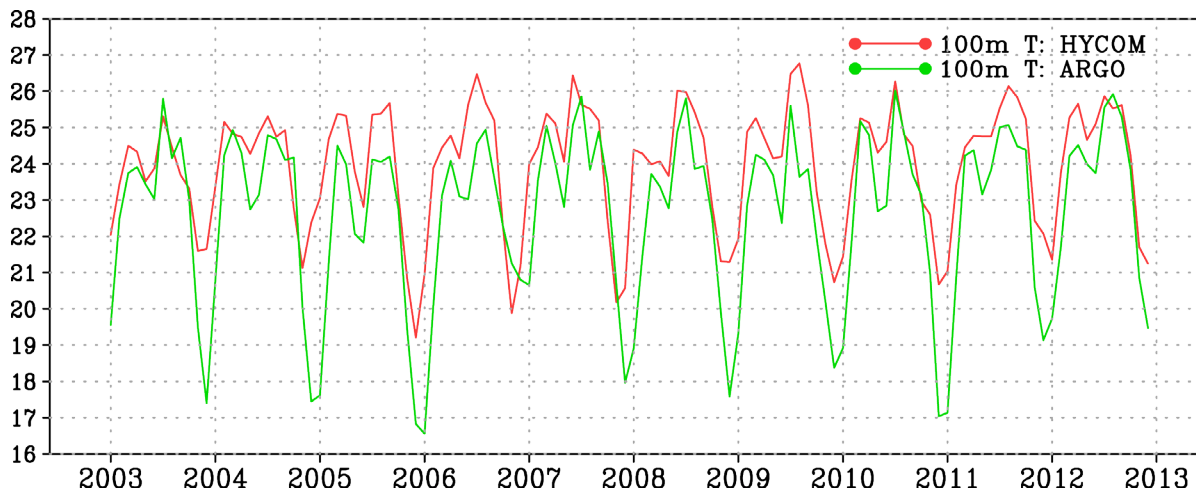
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*Fig. 1. Climatological (2003-2012) total velocity vectors ( $cm\ s^{-1}$ ) at 15 m from 0.08° HYCOM for April (left) and May (right).*



**Fig. 2.** Amplitude (cm) and phase (°) of the annual cycle of sea surface height anomaly from AVISO altimeter observations (left) and 0.08° HYCOM (right) for 2003-2012.



**Fig. 3.** Time series of potential temperature (°C) at 100 m from HYCOM and Argo for 2003-2012 averaged over 55°-60°E and 3°-5°N.