

Flow Through the Straits of the Philippine Archipelago Simulated by Global HYCOM and EAS NCOM

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LONG-TERM GOALS

We are collaborating with other DRI participants to better evaluate and understand the dynamics seen in observations and model results within the Philippine Archipelago, a strategic region with numerous straits. The model results come from the .08° and .04° global HYbrid Coordinate Ocean Model (HYCOM) and .088° East Asian Seas (EAS) Navy Coastal Ocean Model (NCOM) nested in global NCOM, the .04° global HYCOM and some finer nests starting in FY09, the others from the outset.

OBJECTIVES

Objectives of our DRI participation are (1) high resolution simulations (with and without tides; with and without data assimilation) that provide a larger scale context for the observations, (2) model-data comparisons with the measurements, (3) studies of observational representativeness in measuring transports through straits, (4) investigation of non-tidal and tidal (barotropic and internal) influences on specific sub-regions of interest, especially where measurements are available, and (5) to provide boundary conditions for nested models.

APPROACH

Ocean models: HYCOM: Traditional ocean models use a single coordinate type to represent the vertical, but no single approach is optimal for the global ocean. Isopycnal (density tracking) layers are best in the deep stratified ocean, pressure levels (nearly fixed depths) provide high vertical resolution in the mixed layer, and σ -levels (terrain-following) are often the best choice in coastal regions. The generalized vertical coordinate in HYCOM allows a combination of all three types (and others), and it dynamically chooses the optimal distribution at every time step via the layered continuity equation. NCOM uses σ -levels when the depth is shallower than 137 m and z-levels, optionally with partial cell topography, elsewhere.

Both models use a C-grid, have scalable, portable computer codes that run efficiently on available DoD High Performance Computing (HPC) platforms, and have a data assimilation capability. EAS NCOM runs with tides and data assimilation and tides have been added as an option in global HYCOM.

Task (1) (corresponding to the list in the objectives) High resolution ocean model simulations: Run HYCOM globally with $.08^\circ$ (9 km equatorial) and $.04^\circ$ (4 km equatorial) resolution, the latter starting in FY09. These are run largely under the sponsorship of partnering and related projects (see Related Projects below). Run simulations with high frequency climatological forcing and run interannually at least over the time frame of the International Nusantara Stratification AND Transport (INSTANT) and DRI data sets. Run HYCOM with and without tides, and with and without data assimilation.

The $.088^\circ$ EAS NCOM (17°S - 52°N , 98°E - 158°E) has been running in real-time with tides and data assimilation since October 2003. It receives boundary conditions from $.176^\circ$ (20 km) equatorial resolution global NCOM (with data assimilation but no tides).

Nested models of the Philippine Seas using HYCOM and NCOM are also planned. Both models already have a robust nesting capability. During the first 3 years the nests would have 3 km resolution and during years 4-5 a Philippine Seas nest in $.04^\circ$ global HYCOM would have 1.5 km resolution. The nested models will be very useful (1) for investigating the impact of resolution on other aspects of the simulations, (2) as boundary conditions for even higher resolution nested models of Philippine Seas subregions run by other DRI participants, and (3) for data representativeness studies. Even same resolution nests will be useful in studying the impacts of tides, different vertical mixing schemes and parameter choices, and data assimilation on other aspects of the Philippine Seas circulation.

Task (2) Model-data comparison studies: Model-data comparisons are used to evaluate and improve the models and to help interpret the data. Data that resolve tidal frequencies and measure straits transports, the vertical structure of the water column, and the nature of its variability are particularly useful. Measures of year-long means and seasonal variability are also valuable. Model output will be archived at measurement locations with sufficient temporal resolution for tides. Measurements used in conjunction with models are vital in studying the roles that tides and other processes play in determining transports through straits and the vertical structure of the water column. Timely access to DRI data will greatly facilitate this process and opportunities for joint publications with other DRI participants are highly desirable, particularly in years 3-5.

Task (3) Studies of data representativeness: All of the models listed in Task (1) can be very useful in assessing the ability of DRI observational arrays to measure integral properties, such as straits transport (both in terms of spatial coverage and length of record), particularly if they perform well in the model-data comparisons (Task 2). They can also be used in estimating appropriate corrections in data analyses. Doing this using a suite of model simulations, rather than just one, and picking models that best match the data should improve the quality of corrections and enhance confidence in the results.

Task (4) Study the interaction of tidal and non-tidal processes in subregions of DRI interest: The Philippine Seas form a region where large amplitude external and internal tides may have a significant impact on the non-tidal circulation and water mass structure. We are particularly interested in

collaborative studies and joint publications on related topics with other DRI participants in subregions of DRI interest.

Task (5) Provide boundary conditions for nested models of other DRI participants: Output from global HYCOM and NCOM are used for this purpose. The boundary conditions can have resolution as fine as 3 km during years 1-3 and as fine as 1 km during years 4-5. Advance coordination is needed to make sure the required time period is archived at the temporal resolution and locations needed. We are also interested in model inter-comparisons to investigate the impact of model resolution and design on the simulation of processes in the vicinity of straits.

WORK COMPLETED

A Hurlburt et al. (2010) manuscript was submitted for publication in the PhilEx special issue of Oceanography scheduled for publication in March, 2011. PhilEx PI, Janet Sprintall from Scripps, was a major collaborator on the paper. H. Hurlburt gave an invited presentation at the Feb. 2010 Ocean Sciences meeting in a session on the "Physical Oceanography of Archipelagos".

Most of the $1/12^\circ$ and $1/25^\circ$ global HYCOM simulations used in the manuscript were run during FY10. These included $1/12^\circ$ global HYCOM simulations 18.0 initialized from the GDEM3 hydrographic climatology (Carnes, 2009) and run 10 model years with monthly climatological atmospheric forcing, 18.2 initialized from 18.0 and run 2003 – mid-2010 with 6-hourly interannual forcing, and 18.5, a repeat of 18.2 with tides initialized from 18.2 in mid-2003. The $1/25^\circ$ global HYCOM simulations were 4.0, a near twin of 18.0, initialized from climatology and 4.1&4.2, a near twin of 18.2, initialized from 4.0. The simulations were run at the Naval Oceanographic Office (NAVOCEANO) using High Performance Computing (HPC) Challenge and non-challenge grants of computer time from the DoD HPC Modernization Program. The climatological atmospheric forcing was derived from the European Centre for Medium-Range Weather Forecasts (ECMWF) 40-year reanalysis (ERA-40) (Kållberg et al., 2004). The interannual simulations used archived operational forcing from the Navy Operational Global Atmospheric Prediction System (Rosmond et al., 2002), but with the long-term annual mean replaced by the long term mean from ERA-40. In all of these atmospheric forcing products the wind speed was corrected using a monthly climatology from the QuikSCAT scatterometer (Kara et al., 2009). See Arbic et al. (2010) for discussion of the implementation of tides in HYCOM. The real-time EAS NCOM system with tides and data assimilation started running in October, 2003 and was turned off in mid-2010.

Daily-averaged top-to-bottom profiles of velocity from HYCOM Exp. 18.2, 2004-2009, at the PhilEx Mindoro mooring location were provided to Janet Sprintall in a collaborative model-data comparison and an effort to estimate the Mindoro Strait transport using data from a single mooring location. Results from HYCOM Exp. 18.5 with tides were provided to Chris Jackson for use in his PhilEx/Oceanography paper. June 2006 results from EAS NCOM were provided to PhilEx participant Cesar Villanoy for use in relating chlorophyll patterns to upwelling on the eastern side of the Bohol Sea and in examining larval dispersal.

RESULTS

The research results discussed here are FY10 results included in the Hurlburt et al. (2010) article for the PhilEx special issue of Oceanography, which also includes results on topics discussed in the Hurlburt and Metzger FY08 and FY09 PhilEx ONR reports.

The circulation within the Philippine Archipelago is an integral component of the large-scale ocean circulation in a region of inter-basin exchange. In that role it provides two significant secondary routes for both the Indonesian throughflow and for the western boundary currents that close the Pacific northern tropical gyre in addition to the Mindanao Current. The deeper route enters the archipelago from the north through Mindoro Strait, after passing through the Luzon Strait and the South China Sea. The second route is very shallow and enters directly from the Pacific via Surigao Strait and passes through Dipolog Strait downstream. Though shallow, the second route is deeper than the pathway entering the Indonesian Archipelago via the Java Sea and Karimata Strait. Both routes through the Philippine Archipelago exit at the southern end via Sibutu Passage and other shallower straits in the adjacent Sulu Archipelago. Within the Philippine Archipelago these "secondary routes" are the dominant contribution to the mean circulation and much of its variability.

The $1/12^\circ$ and $1/25^\circ$ global HYCOM simulations and archived real-time data-assimilative nowcasts from EAS NCOM, nested in global NCOM, were used to study the circulation in the Philippine Archipelago within the context of the global ocean circulation. The global simulations demonstrate that 2004 and 2008, the latter the central year of the PhilEx observational program, were extreme opposite anomalous years, highlighted by anomalously strong southward flow through Mindoro in 2004 and mean northward flow in and above the thermocline during 2008 (Figure 1). Associated opposite sea surface height anomalies in the western Pacific were verified by satellite altimetry (Figure 2). The sea surface height anomalies had little effect on the transport of the Surigao-Dipolog route, which demonstrated weak interannual variability. These results indicate that the inflow through Mindoro Strait is the primary external source of interannual variability in the Philippine Archipelago circulation.

The 22 December 2007 to 18 March 2009 data from a single PhilEx mooring in Mindoro Strait in combination with HYCOM simulation results allow the first estimate of transport through Mindoro Strait using in situ data. The model helped extend the data across the strait and beyond the anomalous period of the observations, giving a mean transport of 0.23 Sv northward during the observation period and a mean of 0.95 Sv southward over 2004-2009 (Figure 3).

The $1/25^\circ$ global HYCOM simulates the observed four-layer flow through Dipolog Strait. The upper cell is driven by entrainment into the westward Surigao-Dipolog surface jet, which has high vertical shear at the base, and the lower cell by vertical mixing in the Bohol Sea, an explanation given by Arnold Gordon in PhilEx cruise reports and at PhilEx DRI meetings. The strength of the lower cell is enhanced by the addition of tides in global HYCOM. All four of the PhilEx cruises observed a robust cyclonic gyre in the Bohol Sea using velocity measurements from a hull-mounted ADCP. This gyre is well-simulated in $1/25^\circ$ HYCOM with 4.4 km resolution in comparison to the cruise velocity measurements and to ocean color imagery, but poorly simulated in the two models with ~ 9 km resolution (Figure 4). The $1/25^\circ$ HYCOM is the first global ocean model with such fine horizontal resolution and more than a few layers in the vertical.

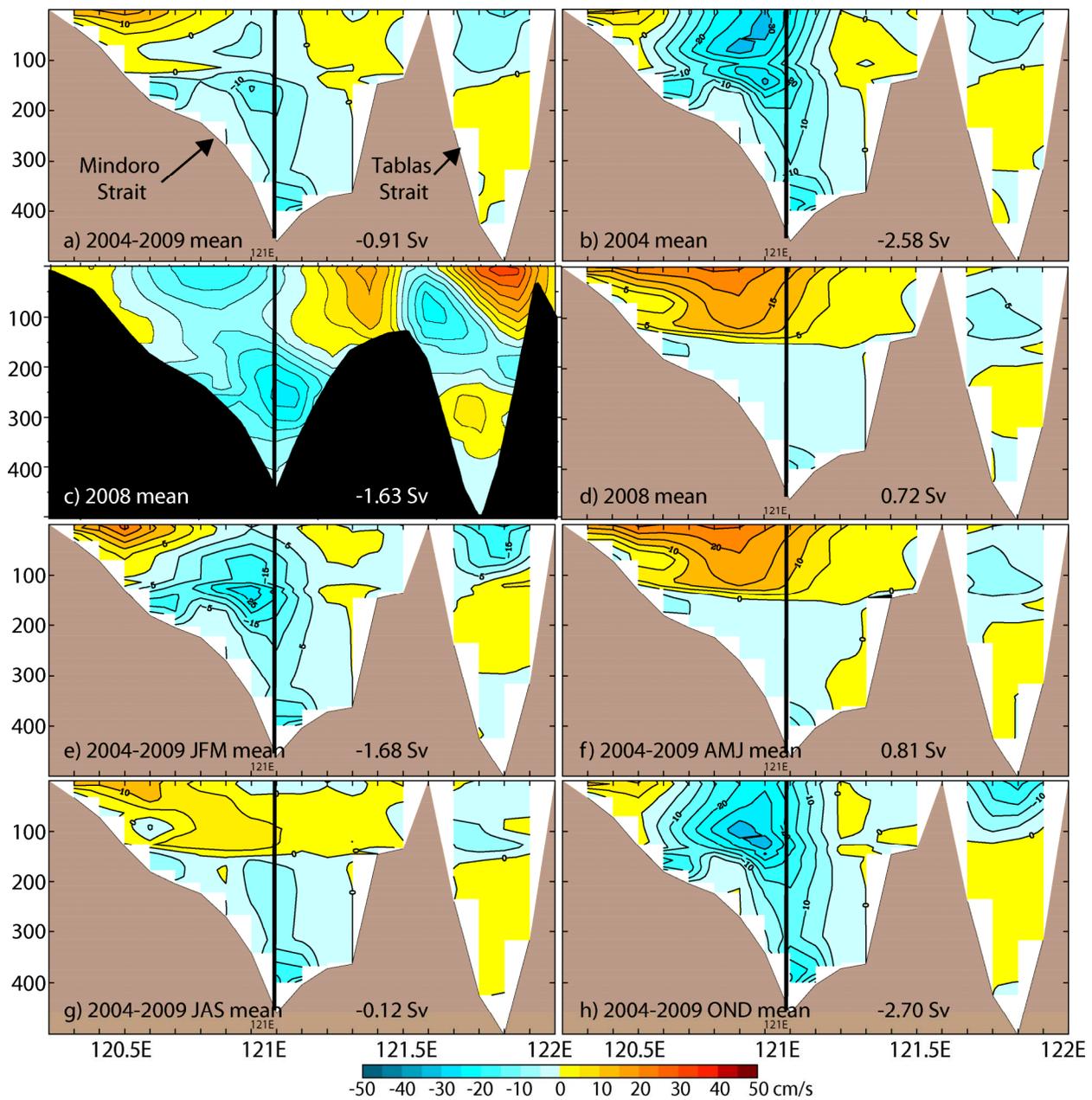


Figure 1. Mean meridional velocity (blue southward) cross-sections at 11.9°N , the latitude of the PhilEx Mindoro mooring (marked with a vertical line on the cross-sections), near the location where Mindoro and Tablas Straits join. The labeled transports are for the entire cross-section and all means are over the time period labeled on the figure panel. (e-h) are seasonal means over 2004-2009 for JFM (January-March, winter), AMJ (spring), JAS (summer), and OND (fall). All are from $1/12^{\circ}$ global HYCOM-18.2, except (c) is from EAS NCOM.

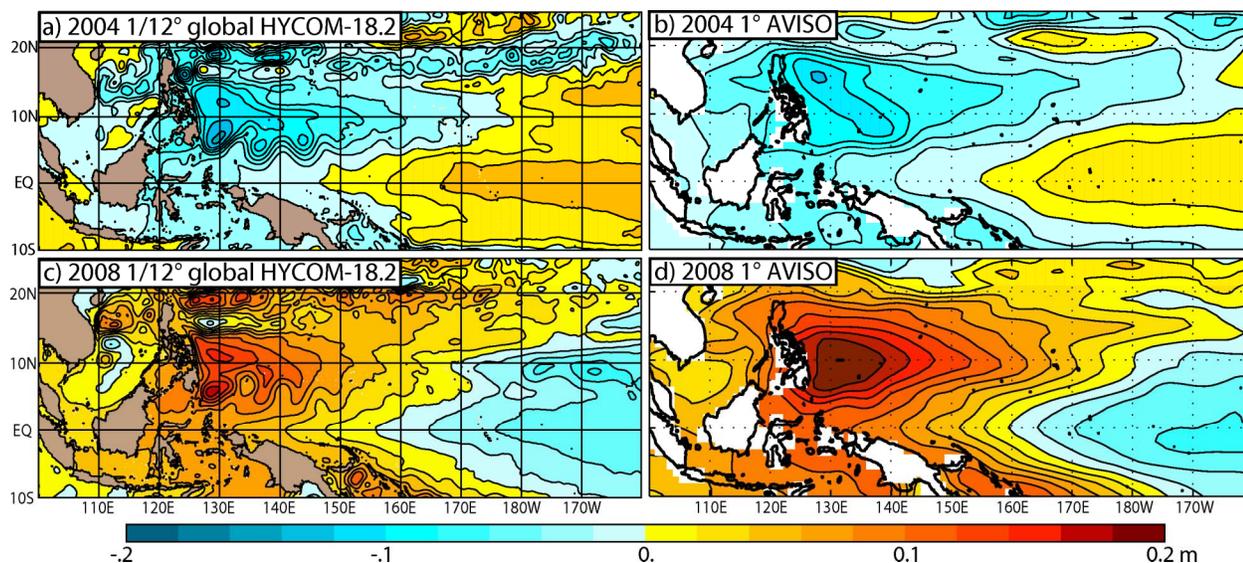


Figure 2. 2004 (a,b) and 2008 (c,d) mean sea surface height (SSH) anomalies from (a,c) 1/12° global HYCOM-18.2 with respect to a 2004-2009 mean and (b,d) 1° AVISO analyses of altimeter data with respect to a 2002-2008 mean. The contour interval is 0.02 m. Both the model and the AVISO analyses of altimeter data show opposite anomalies in 2004 and 2008, the latter the central year of the PhilEx observational effort.

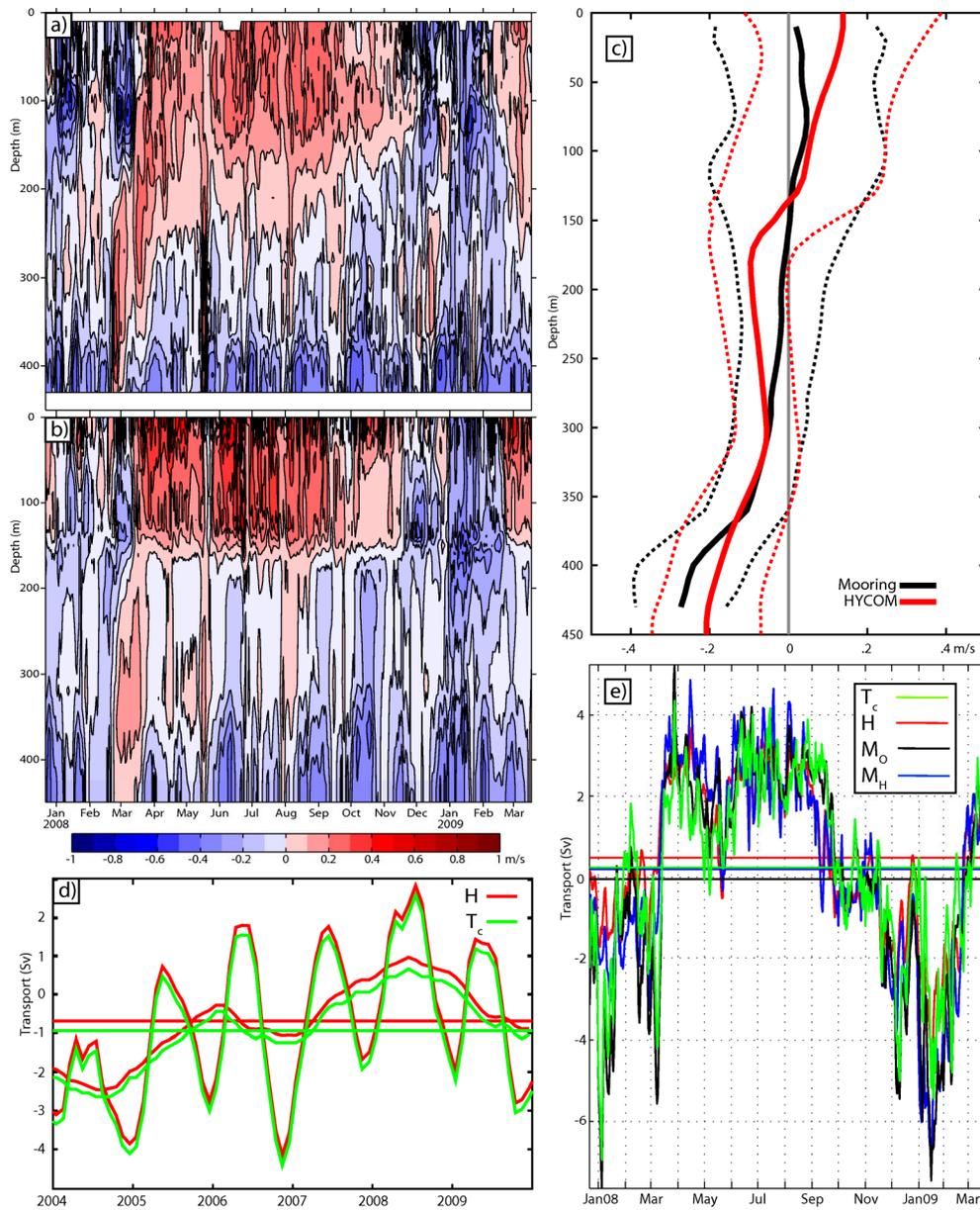


Figure 3. Mindoro Strait comparisons of daily mean meridional velocity versus depth (negative southward) over the observational period with dates labeled at the beginning of each month or year, from (a) the mooring and (b) $1/12^\circ$ global HYCOM-18.2 (in $m\ s^{-1}$ with a $0.1\ m\ s^{-1}$ contour interval). (c) Mooring and model means (solid lines) and standard deviations (dashed) of meridional velocity component versus depth. Transport (in Sv) versus time over (d) 2004-2009 (monthly mean with a 1-2-1 filter, 1-year running mean, and 2004-2009 mean transports from (H) (red) $1/12^\circ$ global HYCOM-18.2 and (T_c) (green) a combined mooring and $1/12^\circ$ HYCOM-18.2 estimate) and (e) the 22 December 2007 – 18 March 2009 period of the observations (daily and observing period mean transports M_o (black) estimated from the mooring alone, M_H (blue) estimated from a co-located HYCOM-18.2 mooring, H (red) from HYCOM-18.2, and T_c (green), a combined mooring and HYCOM-18.2 estimate).

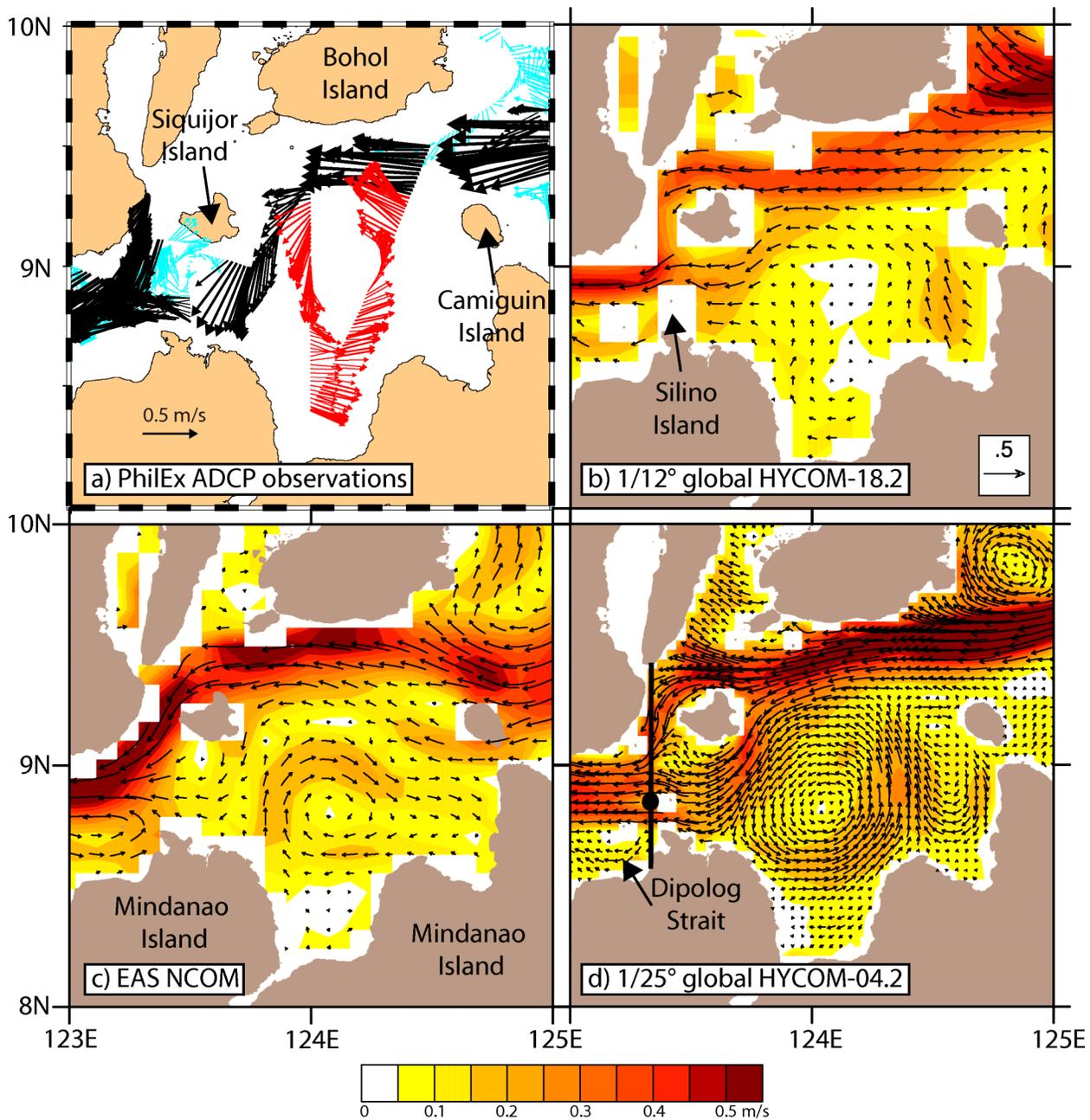


Figure 4. (a) ADCP velocity vectors at 21 m depth observed in the western Bohol Sea during 1-8 March 2009 versus 1-8 March 2009 mean currents at 20 m overlaid on speed from (b) 1/12° global HYCOM-18.2, (c) EAS NCOM, and (d) 1/25° global HYCOM-4.2. The reference vector for velocity is 0.5 m/s and mean speed is contoured at 0.05 m/s intervals. The black dot in (d) denotes a PhilEx mooring location in the lee of a small rise capped by Silino Island and the black line the longitude of the mooring. The observed mean speed of the westward jet at ~20 m depth (black vectors in panel a) is 0.56 m/s versus 0.31 m/s in 1/12° HYCOM-18.2, 0.45 m/s in 1/25° HYCOM-4.2, and 0.46 m/s in EAS NCOM. Within the cyclonic gyre (red vectors) the observed mean speed is 0.36 m/s versus 0.15 m/s in 1/25° global HYCOM-4.2. To avoid a biased comparison, the observational result was chosen before the contemporaneous model results were extracted.

IMPACT/APPLICATIONS

The $.04^\circ$ (3.5 km mid-latitude) resolution, first used in some FY09 global HYCOM simulations, is the highest so far for a global ocean model with high vertical resolution. As demonstrated in this report, the resolution increase from $.08^\circ$ to $.04^\circ$ in global HYCOM has a major impact on our ability to simulate the circulation in a complex archipelago with interior seas, numerous small islands, and narrow straits within a global ocean model. However, improved knowledge of the topography and sill depths of the Philippine Archipelago is essential because hydraulic control makes the flow through the straits very sensitive to the accuracy of the straits topography and sill depths. A global ocean prediction system, based on $.04^\circ$ global HYCOM with tides, is planned for real-time operation starting in 2012. At this resolution, a global ocean prediction system can directly provide boundary conditions to nested relocatable models with ~ 1 km resolution anywhere in the world, a goal for operational ocean prediction at NAVOCEANO.

In the ONR PhilEx DRI, output from $.04^\circ$ and $.08^\circ$ global HYCOM and $.088^\circ$ EAS NCOM are providing the larger scale context of the circulation in the Philippine Seas and real-time nowcast and forecast output from data-assimilative $.08^\circ$ global HYCOM has been used as boundary conditions for a real-time regional ROMS system run by the group at Rutgers University.

TRANSITIONS

Global NCOM is operational at NAVOCEANO and the $.08^\circ$ global HYCOM prediction system is running in a real-time preoperational mode. Operational testing is planned in FY11. The global HYCOM system is receiving 6.4 SPAWAR funding (see below) for evaluation/validation.

RELATED PROJECTS

As partnering funding, we support related Indonesian/Philippines Seas work using two existing 6.1 NRL Base projects: “Global remote littoral forcing via deep water pathways” (H. Hurlburt, PI) and “Dynamics of the Indonesian throughflow (ITF) and its remote impact” (E.J. Metzger, PI). Related projects supporting global HYCOM also substantially benefit this DRI project. These include the multi-institutional effort to develop a next generation eddy-resolving global ocean prediction system using HYCOM. This effort was supported by the FY04-08 NOPP project, “U.S. GODAE: Global Ocean Prediction with the Hybrid Coordinate Ocean Model (HYCOM)” (<http://www.hycom.org>) (H. Hurlburt, NRL PI), which ended on 31 Dec 2008, and a related 6.4 project, “Large Scale Prediction” (E.J. Metzger, PI). The computational effort is strongly supported by DoD HPC Challenge and non-challenge grants of computer time. In FY10 $.04^\circ$ and $.08^\circ$ global HYCOM ran under an FY09-11 DoD HPC Challenge grant.

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PUBLICATIONS

- Hurlburt, H.E., E.J. Metzger, J. Sprintall, S.N. Riedlinger, R.A. Arnone, T. Shinoda, and X. Xu. 2010. Circulation in the Philippine Archipelago simulated by 1/12° and 1/25° global HYCOM and EAS NCOM. *Oceanography* (submitted for a special issue on the PhilEx DRI).