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Eddy Resolving Global Ocean Prediction including Tides

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LONG-TERM GOALS

Use the HYbrid Coordinate Ocean Model (HYCOM) with tides, dynamic sea ice, and data assimilation in an eddy-resolving, fully global ocean prediction system with 1/25° horizontal resolution that will run in real time at the Naval Oceanographic Office (NAVOCEANO) starting in 2012. The model will include shallow water and provide boundary conditions to finer resolution coastal models that may use HYCOM or a different model.

OBJECTIVES

To develop, evaluate, and investigate the dynamics of 1/25° global HYCOM (HYbrid Coordinate Ocean Model) with tides coupled to CICE (Los Alamos Community Ice CodE) with atmospheric forcing only, with data assimilation via NCODA (NRL Coupled Ocean Data Assimilation), and in forecast mode. Also to incorporate advances in dynamics and physics from the science community into the HYCOM established and maintained within the Navy.

APPROACH

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. HYCOM use a C-grid, has scalable, portable computer codes that run efficiently on available DoD High Performance Computing (HPC) platforms, and has a data assimilation capability.

Global HYCOM with 1/12° horizontal resolution at the equator (~7 km at mid-latitudes) is the ocean model component of the eddy-resolving nowcast/forecast system currently running in real time in the operational queue on the Cray XT5 at the Naval Oceanographic Office (NAVOCEANO). It provides nowcasts and forecasts of the three dimensional global ocean environment. HYCOM is coupled to the Los Alamos Community Ice CodE (CICE) (Hunke and Lipscomb, 2004) via the Earth System Modeling Framework (ESMF) (Hill et al., 2004), although currently for Arctic-only configurations. Coupling between the ocean and sea ice models more properly accounts for the momentum, heat and salt fluxes at the ocean/ice interface. The final component of the nowcast/forecast system is the NRL Coupled Ocean Data Assimilation (NCODA) which is a multivariate optimal interpolation scheme that assimilates surface observations from satellites, including altimeter and Multi-Channel Sea Surface Temperature (MCSST) data, sea ice concentration and also profile data such as XBTs (expendable bathythermographs), CTDs (conductivity temperature depth) and ARGO floats (Cummings, 2005). By combining these observations via data assimilation and using the dynamical interpolation skill of the model, the three dimensional ocean state can be accurately nowcast and forecast.

The principal goal of this project is to perform the necessary R&D to prepare to provide a next-generation ocean nowcast/forecast system with real time depiction of the three-dimensional global ocean state at fine resolution (1/25° on the equator, 3.5 km at mid-latitudes, and 2 km in the Arctic). A major sub-goal of this effort is to test new capabilities in the existing 1/12° global HYCOM nowcast/forecast system and to transition some of these capabilities to NAVOCEANO in the 1/12° system, and others in the 1/25° global system. The new capabilities support (1) increased nowcast and forecast skill, the latter out to 30 days in many deep water regions, including regions of high Navy interest such as the Western Pacific and the Arabian Sea/Gulf of Oman, (2) boundary conditions for coastal models in very shallow, and (3) external and internal tides, the latter will initially be tested at 1/12°, to minimize computational cost, but will transition to NAVOCEANO only in the 1/25° system because at this resolution it will replace regional models with tides (all these will greatly benefit from the increase to 1/25° resolution). In addition to the NRL core tasking covered here, this effort will collaborate with a core team of similar size at FSU COAPS, with other parties interested in HYCOM development, and ONR field programs to test and validate the model in different regions and different regimes. Demonstrated advancements in HYCOM numerics and physics from all sources will be incorporated through this project.

WORK COMPLETED

The first 1/25º global HYCOM simulations (3.5 km resolution at mid-latitudes) were run last year with climatological 6-hourly atmospheric forcing. This year we extended the simulation for 2003-2010 with 3-hourly NOGAPS atmospheric forcing, but still without data assimilation. It was run at NAVOCEANO using an HPC Challenge grant of computer time from the DoD HPC Modernization Program. For comparison, a near twin 1/12 º global HYCOM simulations was also integrated 2003-2010 with the same NOGAPS forcing.

We ran the very first eddy resolving (1/12 º) 3-D global ocean simulation with standard atmospheric forcing and tides in FY08 (Arbic et. al., 2010). The primary technical challenge in making this work was the separation of tidal and non-tidal near-bottom currents, because there is an additional tidal drag based on bottom roughness that should not be applied to non-tidal flow. However, on further analysis it became clear that in a few regions of very rough bathymetry the initial simulation exhibited large non-physical mean near-bottom flows. In addition, the original case with tides was designed as an exact twin of a relatively old inter-annually forced case. This year we performed a second multi-year simulation with an improved bottom tidal drag field that does not exhibit any significant non-physical effects on the mean near-bottom flows. It is also an exact twin of the 2003-2010 NOGAPS forced case mentioned above.

The Arctic Cap Nowcast/Forecast System (ACNFS) consists of the subset of our tri-pole 1/12° global HYCOM domain that is north of 40°N (3.5 km resolution near the North Pole, 6.5 km at 40°N) coupled to the Los Alamos Community Ice CodE (CICE) via the Earth System Modeling Framework (ESMF) with NCODA 3DVAR data assimilation of ocean state and sea ice concentration. It has run in hindcast mode from July 2007 and in real time since June 2010. It has been approved by its Validation Test Panel to be ready for operational testing at NAVOCEANO.

RESULTS

Figure 1 compares the ice concentration from ACNFS to sea ice concentration obtained from SSM/I for September 15, 2007. ACNFS assimilates SSM/I ice concentrations between 0% and 40%, so the two fields are not independent. However, the solid black line is an independent ice edge analysis produced by the National Ice Center (NIC), and all three are in close qualitative agreement. An ACNFS-like system without data assimilation would exhibit similar ice coverage (not shown), but differ significantly in detail particularly in the summer.

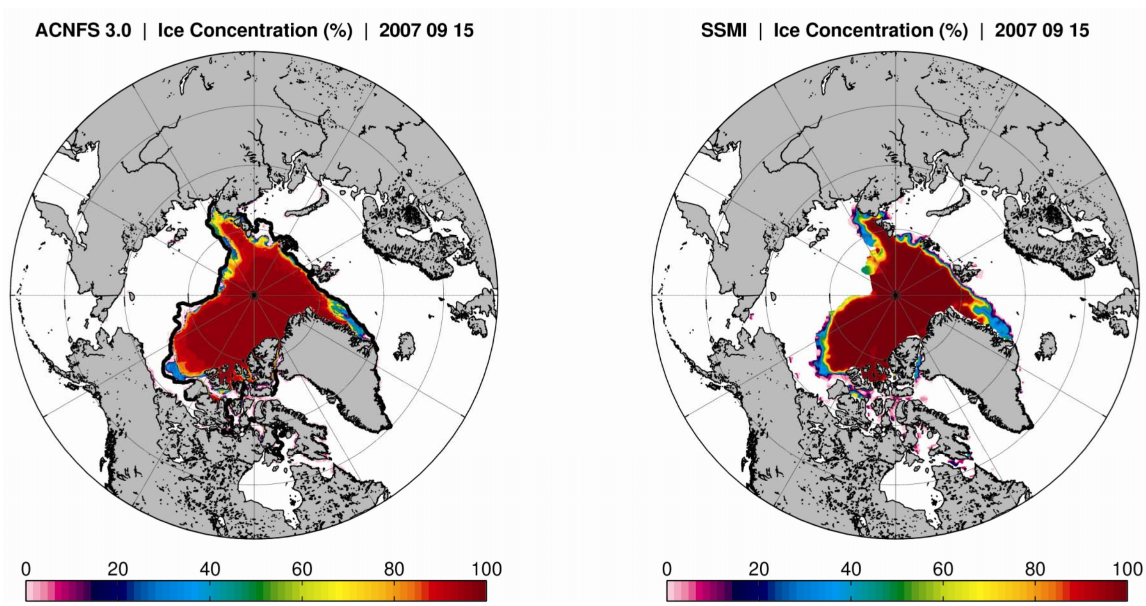

Figure 1. Ice Concentration (in percent) from a) ACNFS and b) SSM/I. Images valid for 15 September 2007. The black line is an independent ice edge from the NIC.

In order for the ACNFS to be declared operational, it must be shown that nowcasts and forecasts are an improvement over the currently operational PIPS 2.0 system (Preller and Posey, 1996). Figure 3 compares ice concentration on August 22, 2009 from ACNFS and PIPS 2.0. PIPS 2.0 couples the Hibler ice model (Hibler, 1979) to the Cox (1984) ocean model north of 30°N with a 17km-35km resolution. Assimilation is performed by direct insertion of SSM/I ice concentration near the ice edge. As part of our validation study, the daily mean distance between the independent, daily observed NIC ice edge and derived model ice edges from PIPS 2.0 and ACNFS were compared for July 2007 – June 2009. Model ice edge locations are those grid points that exceed a certain threshold value for ice concentration and that also have a neighboring point that falls below that value. PIPS 2.0 is limited to a minimum threshold of 20% since open water in PIPS 2.0 is defined by concentrations of 15% or less. Daily means are calculated from the distances between each NIC observed point and the nearest model-derived ice edge location. Figure 2 shows the daily mean distances from July 2007 to June

2009 between NIC and model ice edge for PIPS 2.0 with a 20% ice concentration threshold and for ACNFS with 20% and 5% ice concentration thresholds. During this time period, the mean distance between the 20% ACNFS ice edge and the NIC ice edge was 76 km, compared to 210 km for the 20% PIPS 2.0 ice edge. This represents a 134 km, or 63%, improvement by ACNFS over PIPS 2.0. Using 5% as the ice concentration cutoff in ACNFS, the mean distance decreased to 61 km, representing a 149 km, or 71% improvement over PIPS 2.0.

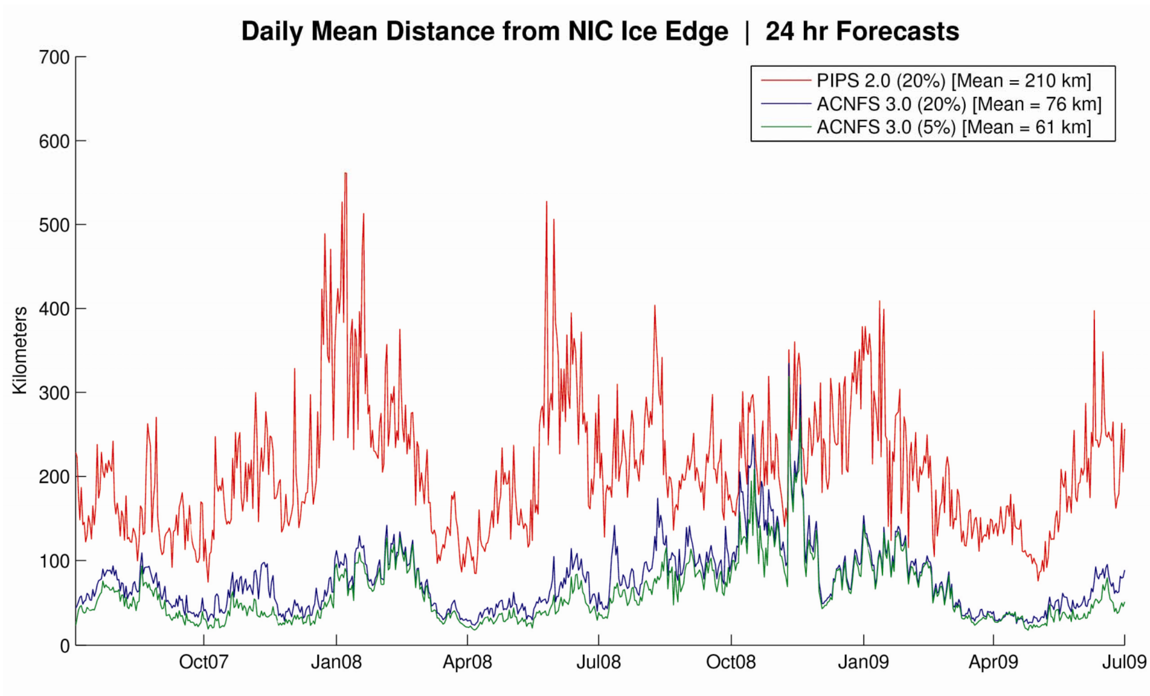

Figure 2. Daily mean distances (km) from the NIC observed ice edge locations to the ice edge locations using the 24 hr forecasts from ACNFS (20%-blue Mean=76km and 5%-green Mean=61km) and PIPS 2.0 (20%-red Mean=210km) for July 2007- June 2009.

Ice leads are narrow cracks in the Arctic that form when ice floes diverge or shear as they move parallel to each other. An ice lead can vary from several meters to over a kilometer. During the evaluation period, areas of convergence/divergence in the central Arctic and north of Greenland during the summer melt period can be seen in ACNFS, but not seen in PIPS 2.0 (Figure 3). Two likely reasons for the inclusion of ice lead formation in ACNFS but not PIPS 2.0 are greater horizontal resolution in ACNFS and more complex thermodynamics and ice layers in ACNFS ice model (CICE). These lead-like features appear to be wind driven and occur usually during the transition period from May through September. These areas of ice convergence/divergence from ACNFS have not been systematically validated but qualitative comparisons with AMSR-E ice concentration suggest at least some of them are realistic.

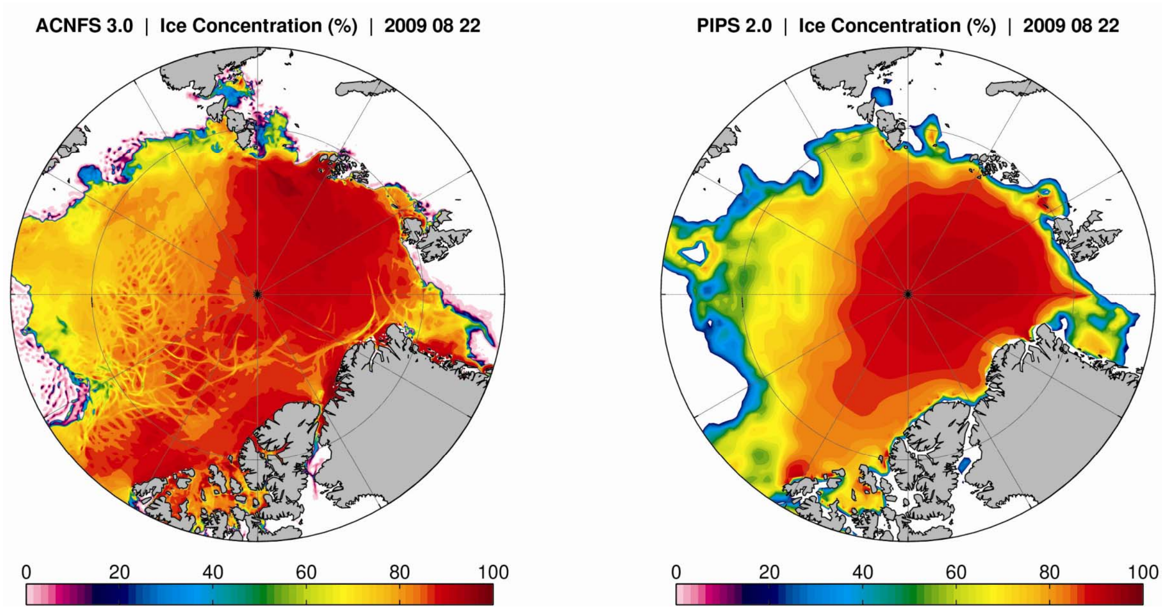

Figure 3. Ice concentration (%) from a) ACNFS and b) PIPS 2.0. Valid August 22, 2009. Areas of lower concentration can be seen just north of Greenland in ACNFS (a) but not in PIPS 2.0 (b).

Modeling the behavior of western boundary currents in ocean general circulation models has been a long standing challenge. Recently, Hurlburt and Hogan (2008) propose that a realistic Gulf Stream pathway requires 1) a sufficiently inertial Gulf Stream and 2) steering by abyssal currents. The abyssal currents could be generated by either the Deep Western Boundary Current (DWBC) associated with the Meridional Overturning Circulation (MOC) or by topographic coupling of the eddy-driven circulation.

In their idealized study, Hurlburt and Hogan (2008) noted that increasing the resolution of the model increased the strength of the eddy driven abyssal circulation to provide the deep steering currents, even in the absence of a DWBC. To investigate the impact of resolution, we perform twin experiments forced by the ERA-40 climatology with a QuikSCAT wind speed correction 1/12° (Figure 4) and 1/25° (Figure 5) resolution. In the upper left hand panels, the 4 year mean sea surface and the GS north wall pathway are shown. In the 1/12° HYCOM, the mean path shows premature separation from the coast with high SSH variability south of the mean GS path, partly associated with excessive meander variability south of Cape Hatteras which is found in both the 1/12° and 1/25° simulations. The separation velocity of the 1/12° simulation at 1.48 m s^{-1} is weaker than the observed range of 1.6 to 2.1 m s^{-1}. The MOC is relatively weak at just over 16 Sv for both simulations and more importantly, the deep limb of the MOC is very shallow consistent with too much Labrador Sea Water and not enough Denmark Straits Overflow Water. The corresponding abyssal circulation is weak in the 1/12° simulation. The key abyssal current at 72°W is weak at less than 4 cm s^{-1} and the key abyssal current at 68.5°W is absent. In the 1/25° HYCOM simulation, the Gulf Stream performance is improved with a more realistic mean sea surface and pathway and a stronger abyssal circulation with both key abyssal currents present. The separation velocity of 1.55 m s^{-1} is at the low end of the observed range.

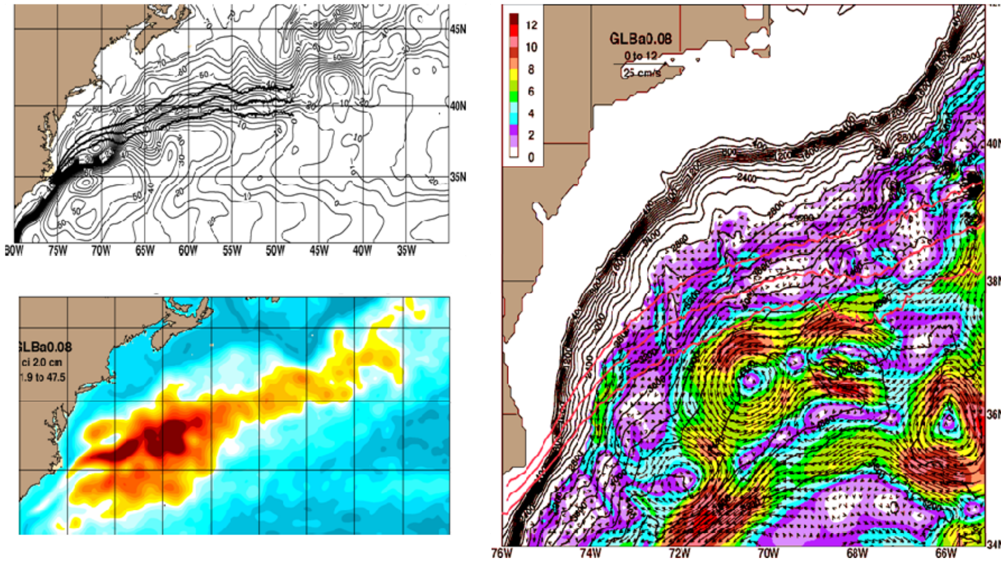

Figure 4. Climatologically forced 1/12° simulation with the mean SSH and mean observed GS pathway in upper left and SSH standard deviation in lower left and layer 27-29 (~3500-4500 m) currents in right panel

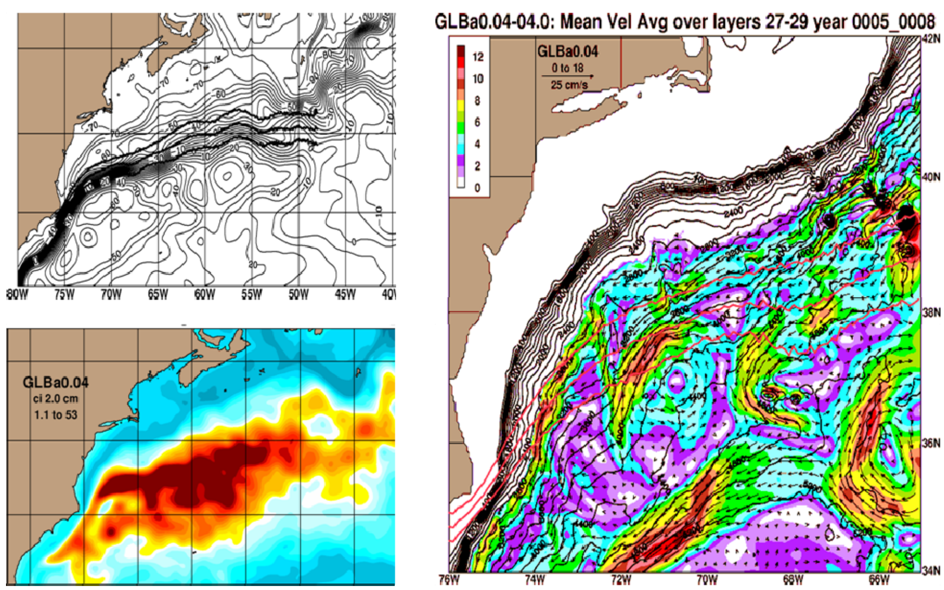

***Figure 5. Climatologically forced 1/25° simulation with the mean SSH and meano bserved GS pathway in upper left and SSH standard deviation in lower left and layer 27-29 (~3500-4500 m) currents in right panel*.**

To investigate the impact of data assimilation, two sets of twin experiments are presented with one set of experiments characterized by weak winds (NOGAPS without QuikSCAT correction) and assimilation of SSH anomalies using the technique of Cooper and Haines (1996) and the second set of experiments using stronger winds (NOGAPS with QuikSCAT correction) and assimilation of SSH anomalies using synthetic temperature and salinity profiles from the Modular Ocean Data Analysis System (MODAS) described by Barron, et al. (2007).

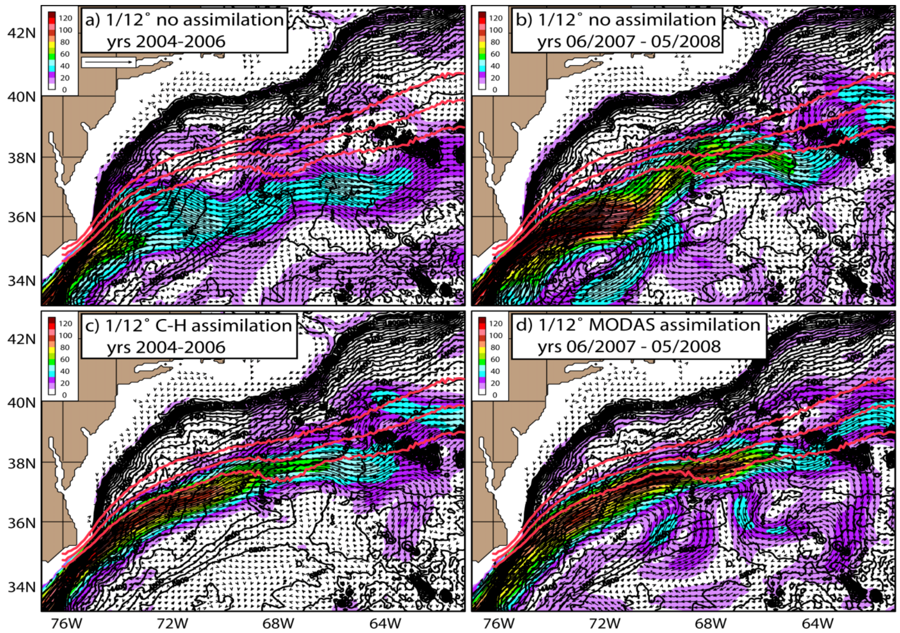

Figure 6. Mean velocities in layer 6 (~25 m) with the mean Gulf Stream pathway ± 1σ overlaid in red and the bathymetry contoured at 200 m intervals from four 1/12° global HYCOM simulations: (a) interannually forced weak Gulf Stream with separation velocity of 1.1 m s^{-1}; (b) interannually forced stronger Gulf Stream with separation velocity of 1.4 m s^{-1}; (c) Cooper-Haines data assimilation twin of the weak Gulf Stream and (d) MODAS synthetic temperature and salinity profile data assimilation twin of the stronger Gulf Stream.

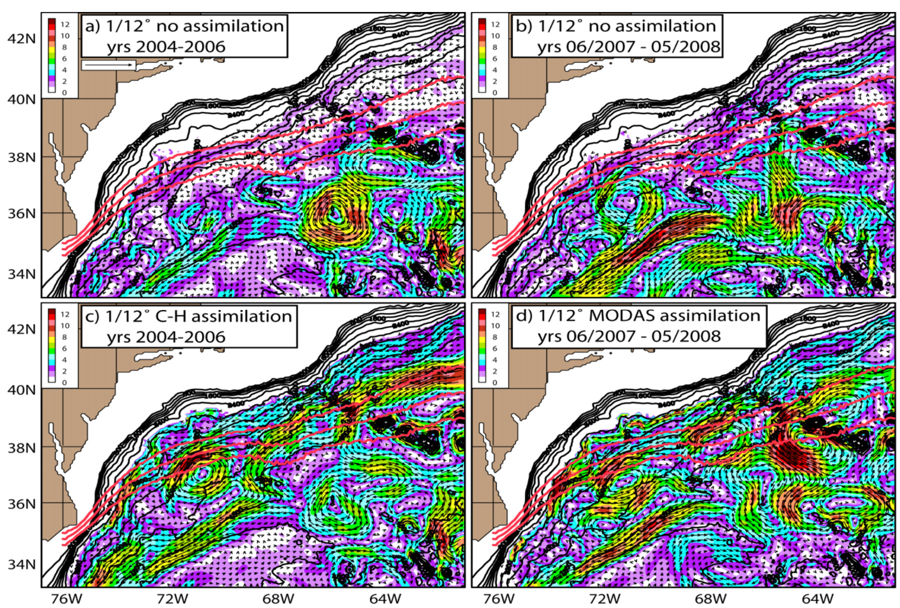

Figure 7. Mean depth averaged velocities in layers 27 to 29 (~3500-4500 m) four 1/12° global HYCOM simulations: (a) interannually forced weak Gulf Stream with separation velocity of 1.1 m s^{-1}; (b) interannually forced stronger Gulf Stream with separation velocity of 1.4 m s^{-1}; (c) Cooper-Haines data assimilation twin of the weak Gulf Stream and (d) MODAS synthetic temperature and salinity profile data assimilation twin of the stronger Gulf Stream.

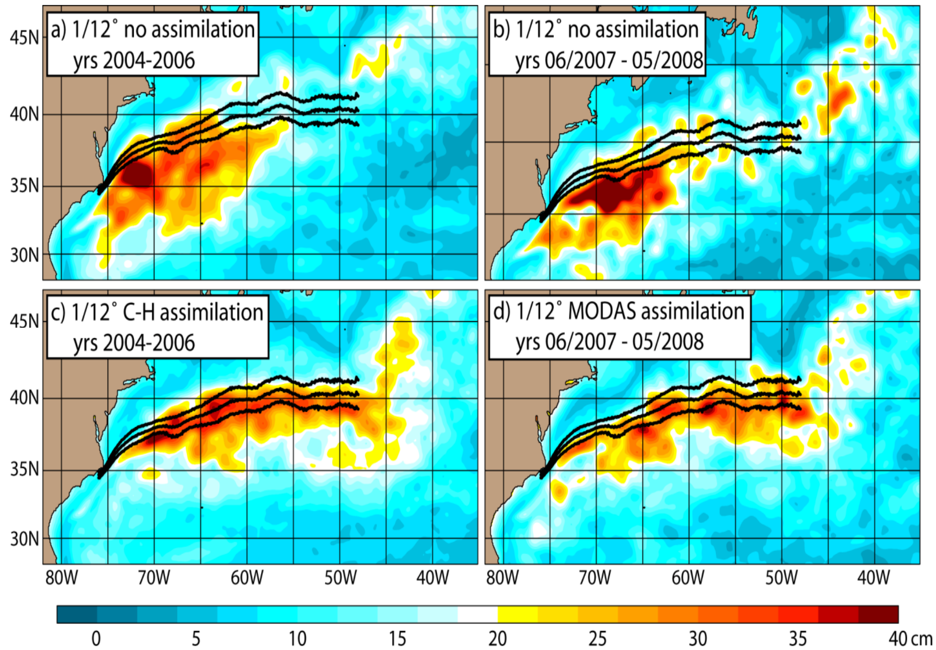

Figure 8. Standard deviation of the sea surface height for four 1/12° global HYCOM simulations: (a) interannually forced weak Gulf Stream with separation velocity of 1.1 m s^{-1}; (b) interannually forced stronger Gulf Stream with separation velocity of 1.4 m s^{-1}; (c) Cooper-Haines data assimilation twin of the weak Gulf Stream and (d) MODAS synthetic temperature and salinity profile data assimilation twin of the stronger Gulf Stream.

The interannual simulation, without the QuikSCAT correction, generates a weak Gulf Stream. The separation velocity is only 1.1 m s^{-1} and the mean core speed decreases rapidly to the east with a speed less than 0.4 m s^{-1} near 72°W. The weak Gulf Stream is associated with weak mean abyssal currents. The key southward abyssal current at 72°W is weak with a speed less than 4 cm s^{-1} and displaced to the south and the key current at 68.5°W is absent along with the associated deep cyclonic gyres as seen in the observations. The strongest abyssal flows are an anticylonic gyre at (36°N, 66°W), which steers the Gulf Stream slightly northward. Near Cape Hatteras, the mean Gulf Stream shows two pathways, one path clinging to the continental slope while another pathway turns almost due east. After separation, the mean pathway lies southward of the mean IR pathway. The MOC is weak and shallow with a transport less than 11 Sv.

The hindcast with weaker uncorrected winds assimilates SSH by adjusting the layer thickness as proposed by Cooper and Haines (1996). In the hindcast, the mean Gulf Stream follows the observed path from the coast out to 68°W. East of 68°W, the flow diverts southward of the observed path, turning sharply northward and splitting as the Stream crosses the New England Seamount Chain (NESC) at 64°W. The SSH variability reproduces all of the features found in the observed altimetric SSH variability. The separation velocity is relatively weak at only 1.1 m s^{-1}. The assimilative Gulf Stream is much stronger to the east with mean speeds of 0.8 m s^{-1} at 70°W and 0.6 m s^{-1} at 65°W. A surprising result is the strong abyssal circulation in the assimilative simulation. The key abyssal currents at 72°W and 68.5°W are present with strengths of 10 cm s^{-1} and 8 cm s^{-1} respectively. The southward flow at 72°W is associated with a cyclonic gyre. The MOC is stronger, with transport greater than 18 Sv, and much deeper than in the non-assimilative simulations. Despite a weaker Gulf

Stream at Cape Hatteras, data assimilation generates a vigorous eddy field which drives a strong abyssal circulation.

The second hindcast uses stronger QuikSCAT corrected winds and assimilation is performed through the Navy Coupled Ocean Data Assimilation System (NCODA) with the SSHA extended into the ocean interior using synthetic profiles of temperature and salinity from MODAS. The mean Gulf Stream follows the observed path extremely well to the east past the NESC to 62°W. The separation velocity is weak, only 1.0 m s^{-1}. However, core speed is a maximum of 1.2 m s^{-1} at 72°W and exceeds 0.65 m s^{-1}at 65°W. The SSH variability reproduces the observed altimetric SSH variability .The eddy driven abyssal circulation is strong, with the key southward abyssal currents exceeding 10 cm s^{-1}. Each of the key currents is associated with a strong cyclonic gyre. The MOC is the strongest, exceeding 20 Sv, and deepest of any of the four simulations. Assimilating the MODAS synthetic profiles appears to generate the most realistic Gulf Stream system with strong eddies along the entire path driving a strong abyssal circulation. Regardless of the assimilation technique, the pathway of the Gulf Stream is improved with stronger penetration to the east, the MOC is deepened and strengthened by 5-6 Sv, the eddy driven abyssal circulation is strengthened and the key abyssal steering currents at 72°W and 68.5°W reproduced.

IMPACT/APPLICATIONS

The 1/25° (3.5 km mid-latitude) resolution is the highest so far for a global ocean model with high vertical resolution. A global ocean prediction system, based on 1/25° 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. Internal tides and other internal waves can have a large impact on acoustic propagation and transmission loss (Chin-Bing et al., 2003, Warn-Varnas et al., 2003, 2007), which in turn significantly impacts Navy anti-submarine warfare and surveillance capabilities. At present, regional and coastal models often include tidal forcing but internal tides are not included in their open boundary conditions. By including tidal forcing and assimilation in a fully 3-D global ocean model we will provide an internal tide capability everywhere, and allow nested models to include internal tides at their open boundaries.

RELATED PROJECTS

There is a related ONR funded project at FSU COAPS, with Eric Chassignet as the principle investigator. Partnering projects at NRL include 6.1 Global Remote Littoral Forcing via Deep Water Pathways, the 6.1 PhilEx DRI project Flow through the straits of the Philippine Archipelago simulated by global HYCOM and EAS NCOM, 6.1 Dynamics of the Indonesian Throughflow (ITF) and its remote impact, 6.2 Full Column Mixing for Numerical Ocean Models, 6.3 Battlespace Environments Institute – ESMF for Atmospheric-Ice-Ocean Coupling and Component Interoperability, 6.4 Large Scale Ocean Modeling, 6.4 Ocean Data Assimilation, and 6.4 Ice Modeling Assimilation from NPOESS. The computational effort is strongly supported by DoD HPC Challenge and NRL non-challenge grants of computer time. In FY10 all 1/25° and some 1/12° global HYCOM cases ran under a FY09-11 DoD HPC Challenge grant.

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