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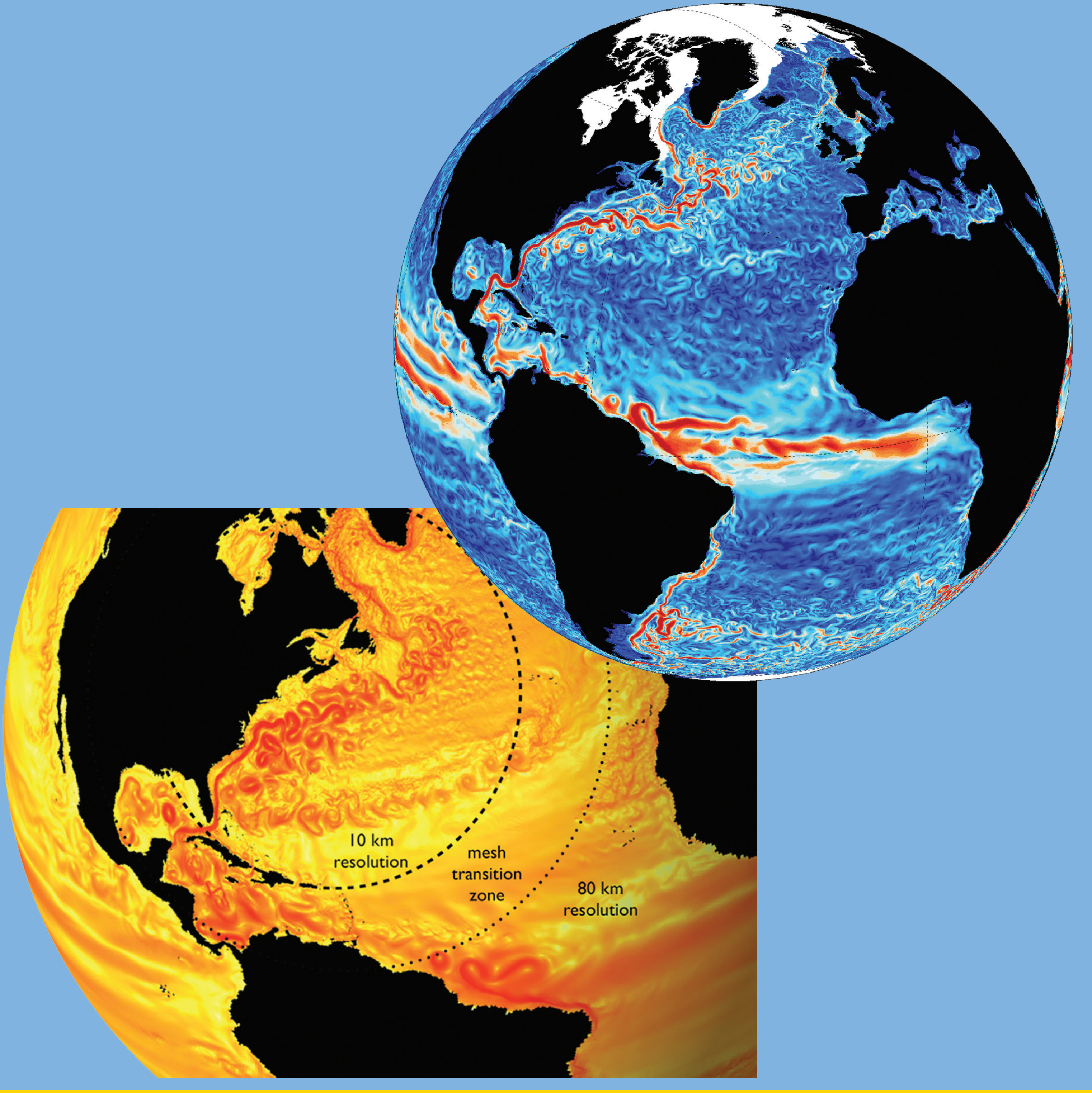

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HYCOM high-resolution eddying simulations

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1. Introduction

Over the past 15 years, a broad partnership of institutions has collaborated on developing and demonstrating the performance and application of eddy-resolving, real-time global and basin-scale ocean prediction systems using the HYbrid Coordinate Ocean Model (HYCOM). This paper is intended to briefly summarise the current status of global high resolution eddy-rich or "eddying" HYCOM simulations and their relevance to high resolution coupled ocean-atmosphere-ice climate simulations. In this context, eddy-rich or "eddying" means that the numerical simulations are eddy-resolving over most of the domain and include an energetic mesoscale eddy field.

None of three main vertical coordinates currently in use (level, isopycnal, or terrain-following) provides universal utility (Griffies et al., 2000; Chassignet et al., 2006), and hybrid approaches have been developed in an attempt to combine the advantages of different types of vertical coordinates in optimally simulating the ocean. The term "hybrid vertical coordinates" can mean different things to different people: it can be a linear combination of two or more conventional coordinates or it can be truly generalised, i.e., aiming to mimic different types of coordinates in different regions of a model domain (Bleck, 2002; Adcroft and Hallberg, 2006). The hybrid or generalised coordinate ocean models that have much in common with isopycnal models are POSEIDON (Schopf and Loughe, 1995) and HYCOM (Bleck, 2002; Chassignet et al., 2003; Halliwell, 2004). Other generalised vertical coordinate models currently under development are the Model for Prediction Across Scales (MPAS; Ringler et al., 2013) and MOM6 (http://www.gfdl.noaa.gov/ocean-model). The default configuration of HYCOM is isopycnic in the open stratified ocean, but makes a dynamically smooth transition to terrain-following coordinates in shallow coastal regions and to fixed pressure-level coordinates in the surface mixed layer and/or unstratified seas. In doing so, the model takes advantage of the different coordinate types in optimally simulating coastal and open-ocean circulation features.

2. Global HYCOM high-resolution eddying simulations

Much of the impetus for integrating high-resolution eddying global numerical simulations comes from the US Navy's interest in advanced global ocean nowcasting/forecasting systems (Metzger et al., 2014a). Within the framework of the multinational Global Ocean Data Assimilation Experiment (GODAE) and under the sponsorship of the National Ocean Partnership Program (NOPP), a broad-based partnership of institutions participated in the development of high resolution data assimilation systems (Chassignet et al., 2009) that were eventually transitioned for operational use by the U.S. Navy at the Naval Oceanographic Office (NAVOCEANO), Stennis Space Center, MS, and by the National Oceanic and Atmospheric Administration (NOAA) at the National Centers for Environmental Prediction (NCEP), Washington, D.C. The current operational global ocean forecast system at NAVOCEANO is referred to as the Global Ocean Forecast System 3.0 (GOFS 3.0). It will be upgraded to GOFS 3.1 in the summer of 2014 to include 3D Variational (3D-VAR) data assimilation methodology, increased vertical resolution in the upper ocean, and two-way coupling to the Los Alamos sea ice model (CICE - Hunke and Lipscomb, 2008). The current HYCOM GOFS configuration has an equatorial resolution of 0.08º (1/12.5ºor ~ 9 km near the equator, ~7 km at mid-latitudes, and ~ 3.5 km near the North Pole). The horizontal resolution will be increased in 2017 to 0.04º (~3.5 km at mid-latitudes) with the addition of tidal forcing (see paper by Arbic et al. 2014, this Issue).

The impact of going to 1/25º horizontal resolution was assessed by Thoppil et al. (2011) who compared the modelled eddy kinetic energy (EKE) with long-term observations from surface drifters, geostrophic currents from satellite altimetry, subsurface floats and deep current meter moorings. Adequately representing mesoscale eddies is key to simulating the mean circulation since the surface and abyssal ocean circulation are strongly coupled through the energy cascades that vertically redistribute the energy and vorticity throughout the entire water column. Although the present generation of eddy-resolving global OGCMs at 1/10° resolve the dominant eddy scale, at this resolution the models significantly underestimate the EKE in the abyssal ocean (i.e., depths greater than 3000 m) (Scott et al., 2010). The 1/12.5° HYCOM is deficient in EKE in both the upper and abyssal ocean by ~21% and ~24% respectively compared to surface drifting buoys and deep current meters. Increasing the model resolution to 1/25º significantly increases the surface and the abyssal EKE to levels consistent with the observations, and clearly demonstrates the need for better representation of upper ocean EKE as a prerequisite for strong eddy-driven abyssal circulation.

Because of the large heat and freshwater transports and interaction with the atmosphere, the Atlantic Meridional Overturning Circulation (AMOC) plays a fundamental role in establishing the mean state and variability of the Earth's climate. Xu et al. (2014) analysed an interannual 1/12.5º global HYCOM simulation forced with the three-hourly, 0.5º Navy Operational Global Atmospheric Prediction System (NOGAPS, Rosmond et al., 2002) to investigate the driving mechanisms behind the variability of the AMOC transport during 2004-2012. The model results are in very good agreement with the RAPID observations at 26.5°N (see Smeed et al. (2014) for the latest results). This is true not only for the total AMOC transports, but also for its components (the Florida Current, the mid-ocean, and Ekman transports). The model simulates well the observed AMOC variability at 26.5o N on intraseasonal, seasonal, and interannual time scales, as well as the observed long-term decrease in the AMOC and the Florida Current transports (3 Sv over 2004-2012). At 41°N, however, the agreement between the model results and the Argo-based observations is mostly due to the Ekman transport and the geostrophic transport is approximately six months out of phase. Mielke et al. (2013) also found a similar phase shift in the seasonal variability of the geostrophic transport between the observations at 41°N and the global simulation of von Storch et al. (2012). This lack of agreement between models and observations suggest that either the models do not adequately represent the ocean dynamics at 41°N and/or the Argo floats are not able to sample adequately the AMOC variability at that latitude. Xu et al. (2014) show that both observations and model results exhibit higher AMOC variability on seasonal and shorter time scales than on interannual and longer time scales. On intraseasonal and interannual time scales, the AMOC variability is often coherent over a wide latitudinal range, but no overall consistent coherent pattern between the Equator and 70°N can be identified on any of these time scales (a,c). On seasonal time scales (Figure 1b), the AMOC variability exhibits two distinct coherent regimes north and south of 20°N, the boundary between the North Atlantic subtropical and tropical gyres, due to different wind stress patterns and variability in the tropics and subtropics. These results highlight the importance of the surface wind in driving the AMOC variability.

3. Reanalysis

The US Navy operational global ocean forecast GOFS model (Metzger et al., 2014) is driven by atmospheric fields from the Navy operational numerical weather prediction model, Navy Global Environmental Model (NAVGEM), and prior to 2013, NOGAPS. As with other operational models, the forecast systems are continually modified and improved. Thus, it is difficult to obtain a consistent evaluation of the model performance over a long period of time. To address this issue, the Naval Research Laboratory has performed a reanalysis of the 1/12.5° global HYCOM forced by the NCEP Climate Forecast System Reanalysis (CFSR) fluxes (Saha et al., 2010, 2014) using the 3D-VAR data assimilation scheme of the Navy Coupled Ocean Data Assimilation (NCODA, Cummings, 2005; Cummings and Smedstad, 2013) for the period 1993 to 2012. The chosen time period spans the modern satellite altimeter era. The altimeter sea surface height (SSH) data provide the largest and most consistent set of observations to constrain the mesoscale eddy circulation in the model. The CFS Reanalysis ends in 2009, but the same model, CFSv2, was used operationally to extend the forcing data set to 2012. In addition to the HYCOM reanalysis, a twin simulation without data assimilation was performed. Over the reanalysis period, the observing system changed substantially. The number of satellite altimeters varied from two to four over the 20-year period and, after 2000, Argo began to provide an increasing number of vertical profiles of temperature and salinity in place of XBT temperature profiles.

The reanalysis was completed in February 2014. As noted by Thoppil et al. (2011), the 20-year CFSR non data assimilative simulation underestimates the EKE at all depths in the ocean compared to the historical surface drifters, geostrophic altimetric EKE, subsurface floats and deep current meters. Preliminary analyses show that data assimilation increases the EKE in both the surface and deep ocean by 10%. However, the reanalysis EKE is still weaker than the observed surface drifter EKE and deep current meter EKE by ~10%. Both the simulation and reanalysis reproduce the 2004-2012 observed AMOC variability. The observed AMOC from the RAPID array has a -0.40 Sv/year trend over the eight years, while the reanalysis and simulation have slightly weaker trends of -0.32 Sv/year and -0.26 Sv/year, respectively. However, none of these interannual trends are significant at the 95% confidence level. Over the 20-year (1993-2012) period, the trends in the AMOC are much weaker at -0.03 Sv/year for the reanalysis and -.14 Sv/year for the simulation. For the 20-year period, the reanalysis mean AMOC is slightly weaker, 19.4 Sv, than the non data assimilative simulation, 19.8 Sv. However, the variability of the AMOC in the reanalysis is greater than the simulation. For the RAPID array period, the reanalysis and simulation AMOC are larger than observed by 2.2 Sv for the reanalysis and 0.9 Sv for the non data assimilative simulation.

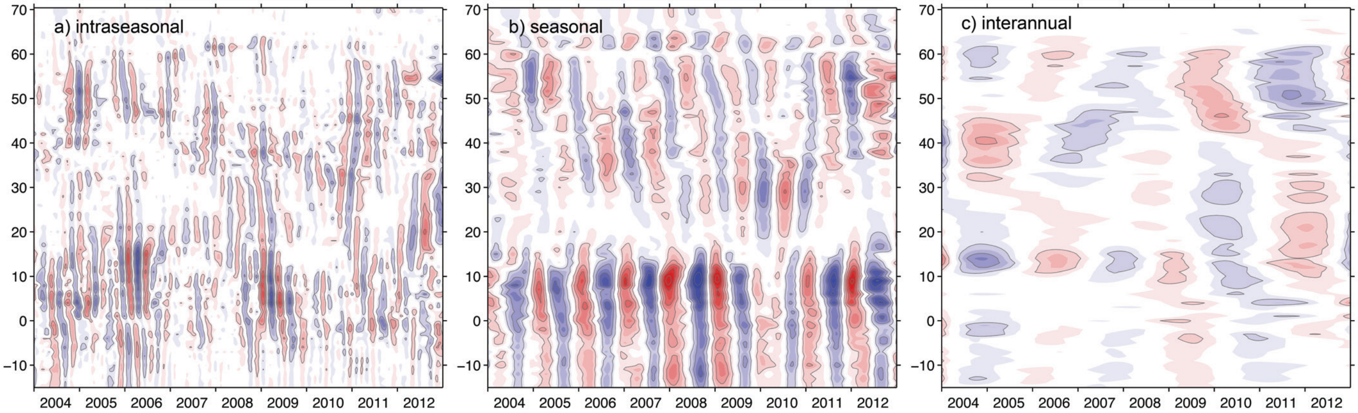

Figure 1. AMOC variability in the 1/12.5° global HYCOM as a function of time and latitude on a) intraseasonal, b) seasonal, and c) interannual time scales. (adapted from Xu et al., 2014).

4. Earth System Prediction Capability (ESPC) program

The Earth System Prediction Capability (ESPC) inter-agency program (Eleuterio and Sandgathe, 2012) was established in 2010 as a coordinated effort to improve collaboration across the sponsored environmental research and operational prediction communities in the US for the development and implementation of improved physical earth system prediction. The ultimate goal of ESPC is to create a high-resolution extended range, coupled atmosphere, ocean, wave, land, and ice to provide more accurate and longer range predictions at the weather-climate interface. The initial Operational Capability is targeted for 2018 (Metzger et al., 2014b) with the following individual components: HYCOM (ocean), WW3 (waves), NAVGEM (atmosphere), NAAPS (aerosol), NAVGEM-LSM (land), and CICE (ice). At that time, daily 10-day forecasts will be performed with a 41 layer 1/25o HYCOM, 70 level T639 (20 km) NAVGEM and 1/8° WW3. Weekly 30-day forecasts using a reduced resolution ocean and wave model and an ensemble of 90-day forecasts with reduced resolution atmosphere, ocean and wave models will also be performed. The component models will be coupled through a mediator layer using the Earth System Modeling Framework (ESMF)/National Unified Operational Prediction Capability (NUOPC) protocols.

For the air-sea momentum exchanges, the momentum flux will include the ocean surface velocity in the shear across the surface, which was surmised by McClean et al. (2011) to improve the performance of the ocean model. Including the ocean shear in the momentum flux improves the penetration of the western boundary currents into the ocean basins, the distribution of EKE at the surface, and the size of the eddy driven recirculation gyres as shown in Figure 2. When using the traditional wind stress estimates from the numerical weather prediction models, the Gulf Stream and Kuroshio do not penetrate as far into the ocean as observed by surface drifters and the recirculation gyre does not extend far enough to the east. Including the ocean surface currents in the wind stress estimation increases the eastward penetration and size of the recirculation gyre. For the Agulhas, as it the case for many ocean models in that resolution range (McClean et al., 2011), too many Agulhas rings are generated that follow a northward pathway into the South Atlantic and the Agulhas Return Current eddies are too weak. Including the ocean shear in the wind stress reduces the number of Agulhas rings and widens their pathways into the South Atlantic and increases the strength and number of Agulhas Return Current eddies.

Preliminary tests of the fully coupled T359 NAVGEM, 1/12.5° HYCOM, and CICE have been performed for the DYNAMO (international experiment to study the initiation of the Madden-Julian Oscillation (MJO)) intensive observation period of November 2011 and for the summer Arctic melt and Antarctic freeze period of July 2011. The 30-day forecasts of the stand-alone atmospheric model were unable to

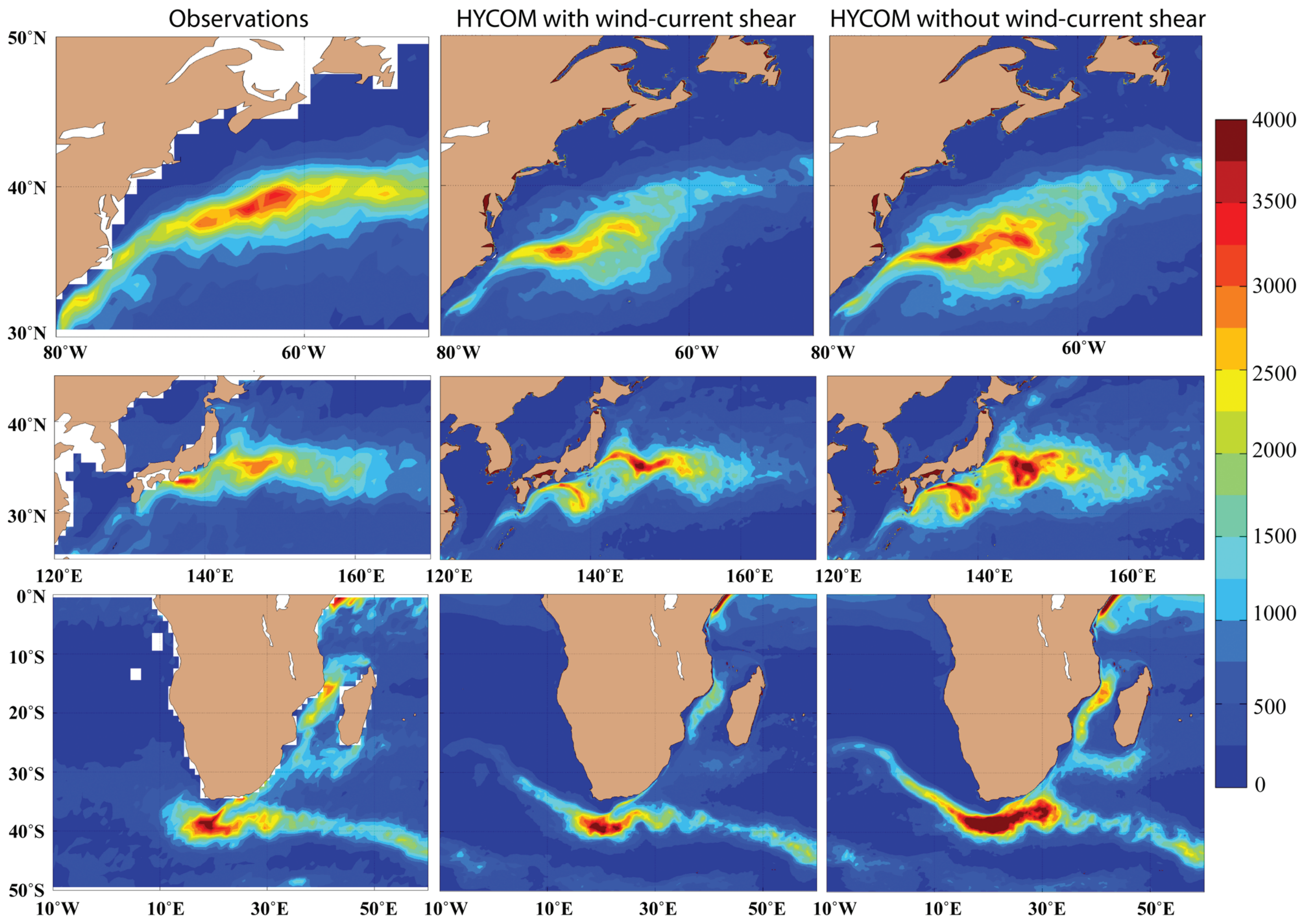

Figure 2. 5-year average surface eddy kinetic energy in cm2s-2 from observations (left panels), 1/12.5° HYCOM simulation that includes the wind-current shear (centre panels), and 1/12.5° HYCOM simulation that does not include the wind-current shear (right panels). The panels from top to bottom show the western boundary current systems of the Gulf Stream, Kuroshio, and Agulhas Current, respectively.

reproduce the onset of the late November MJO, the eastward propagation of the MJO, and the observed tropical rainfall patterns. The ESPC coupled model, on the other hand, developed an MJO in late November, but the eastward propagation was too weak and significant differences in the rainfall patterns remained. For the ocean, the global sea surface temperature rms error between the coupled model and the standalone analysis remained below 1 °C for the 30-day period. Further testing with new convection schemes in the atmosphere are underway. Climate simulations at that resolution will not be feasible for the foreseeable future, but a great deal can be learned about the coupled model behaviour through these short-term experiments.

Acknowledgements

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