Evaluation of a global eddy-permitting hybrid coordinate ocean model

CHENG Yue-Liang\(^{a,b}\), YAN Chang-Xiang\(^{a,c}\), ZHU Jiang\(^{a,b}\) and LI Yi-Neng\(^{d}\)

\(^{a}\)International Center for Climate and Environment Sciences, Institute of Atmospheric Physics, Chinese Academy of Sciences, Beijing, China; \(^{b}\)College of Earth Science, University of Chinese Academy of Sciences, Beijing, China; \(^{c}\)State Key Laboratory of Acoustics, Institute of Acoustics, Chinese Academy of Sciences, Beijing, China; \(^{d}\)South China Sea Institute of Oceanology, Chinese Academy of Sciences, Guangzhou, China

ABSTRACT

A historical run (1993–2014) of a global, eddy-permitting, hybrid coordinate ocean model (HYCOM) is evaluated against observations. The authors evaluate several metrics in the model, including the spatial distribution of sea surface temperature (SST), the zonally averaged seasonal cycle of SST, the variability of the sea level anomaly (SLA), the zonally and meridionally averaged temperature and salinity, and the equatorial undercurrent. It is found that the simulated seasonal cycle of SST is 0.2–0.8 stronger than observed at midlatitudes. The modeled SST is 0.29°C warmer than the observed for the global ocean. The structure of the subsurface temperature and salinity is similar to the observed. Moreover, the variability of SLA exhibits the same pattern as observed. The modeled equatorial undercurrent in the Pacific Ocean is weaker than observed, but stronger than the ECO reanalysis product. Overall, the model can reproduce the large-scale ocean states, and is suitable for analyses seeking to better understand the dynamics and thermodynamics of the upper ocean, as well as ocean variability.

1. Introduction

The quality of ocean general circulation models (OGCMs) has developed substantially over the past 20 years, including improved numerical techniques, sub-grid parameterizations, surface forcing, and bathymetry. Another important step has been supercomputing technology, which has allowed models to be run at very high resolutions. However, for global- or basin-scale ocean simulations, too high a resolution can still create a heavy computational burden. The eddy-permitting scale is an intermediate resolution that can resolve parts of mesoscale eddies with relatively low calculation effort, and many studies have proved that this approach is capable of meeting most of the necessary ocean conditions (Rattan et al. 2010; Woloszyn, Mazloff, and Ito 2011; Jansen et al. 2015).

Owing to the diverse stratification states of sea waters, an ideal OGCM should pick the appropriate vertical coordinate everywhere in the ocean, as pointed out by model comparison exercises performed in Europe (Dynamics of North Atlantic Models, Barnard et al. 1997) and in the U.S. (Data Assimilation and Model Evaluation Experiment, Lai, Qian, and Glenn 1994). HYCOM was developed from the Miami Isopycnal Coordinate Ocean Model, and can choose isopycnal, terrain-following, or z-level coordinates according to the conditions (Bleck 2002; Chassignet et al. 2007). In view of the advantages of hybrid coordinates, Kara et al. (2008) used multiple statistical metrics to evaluation HYCOM and revealed it has the ability to replicate past SST events in climatological and interannual simulations. Based on a global HYCOM simulation, Metzger et al. (2010) reported high correlation between the modeled and observed Indonesian Throughflow. Through a coupled climate model that included HYCOM, Persechino et al. (2012) found that the variability of the Atlantic Meridional Overturning Circulation might be...
associated with low-frequency North Atlantic Oscillation. Besides ocean-state research, HYCOM has also been used in some operational systems, such as the HYCOM consortium sponsored by the National Ocean Partnership Program, which has succeeded in applying real-time global- and basin-scale prediction systems (Chassignet et al. 2009; Metzger et al. 2014); and the TOPAZ system, developed by the Nansen Environmental and Remote Sensing Center, which represents the main workhorse of the Arctic Marine Forecasting Center of the MyOcean project (Bertino, Lisæter, and Scient, 2008; Sakov et al. 2012).

The primary objective of this paper is to describe and evaluate the results from a global-scale, eddy-permitting HYCOM simulation. Details of the model configuration are described in section 2. The historical run is evaluated in section 3. Conclusions are presented in section 4.

2. Model configuration and observations

2.1 Model configuration

Version 2.2 of HYCOM is used. The model domain has global coverage. The horizontal model grid is created by a conformal mapping with the poles shifted to Eurasia and the southern pole. It has $1800 \times 1200$ horizontal grid points with grid spacing of approximately 17–25 km.

The model adopts hybrid vertical coordinates and has 30 hybrid layers. The reference potential densities are 10.1, 10.2, 10.3, 10.4, 10.5, 30.83, 31.11, 31.73, 32.19, 32.68, 33.36, 33.87, 34.22, 34.66, 35.07, 35.50, 35.83, 36.07, 36.25, 36.38, 36.47, 36.65, 36.82, 36.93, 37.01, 37.08, 37.15, 37.19, 37.21 and 37.24. The top 30 hybrid layers. The reference potential densities of approximately 17–20°N, are 10.1, 10.2, 10.3, 10.4, 10.5, 30.83, 31.11, 31.73, 32.19, 32.68, 33.36, 33.87, 34.22, 34.66, 35.07, 35.50, 35.83, 36.07, 36.25, 36.38, 36.47, 36.65, 36.82, 36.93, 37.01, 37.08, 37.15, 37.19, 37.21 and 37.24. The top five light densities ensure they remain as z-coordinates (Wan, Zhu, and Bertino 2008). The K-profile parameterization mixing scheme is employed in the model (Large, McWilliams, and Doney 1994). The model topography is derived from ETOP05(NOAA 1988).

The model is initialized using the climatological temperature and salinity from the Polar Science Center Hydrographic Climatology (Steele, Morley, and Ermold 2001) at rest. First, we carry out a 100-year spin-up experiment driven by the climatological forcing. Then, we perform a historical run (1993–2014) forced by high-frequency (6-h) forcing fields including wind, temperature, humidity, pressure and precipitation from the ERA-Interim dataset (Dee et al. 2011). The ERA-Interim data are used to calculate the surface flux (Drange and Simonsen 1996). In addition, the surface salinity flux includes both the relaxation term of sea surface salinity and the fresh flux caused by precipitation, evaporation, and run-off.

2.2 Observations

Five datasets are used for the evaluation. OISST data (Reynolds et al. 2007), with a resolution of $0.25° \times 0.25°$, are used to assess the SST. Temperature and salinity from version 2 of the World Ocean Atlas 2013 (WOA13) are employed to evaluate the subsurface ocean states. The altimetry data on a $1/4^\circ$ grid produced by AVISO (Ducet, Traon, and Reverdin 2000) are used for the sea level anomaly (SLA) evaluation. The ECCO reanalysis product (Wunsch et al. 2009) along with TAO (McPhaden et al. 1998) and TRITON (Kuroda 2002) observations are used for examining the zonal current in the equatorial Pacific.

3. Model evaluation

3.1 Sst

SST is an important ocean variable that can affect the exchange of heat, momentum, and water vapor between air and sea (Curry et al. 2015), widely used for studying climate change and ocean forecasting. In this section, we mainly focus on the SST seasonal cycle and the El Niño-related variability.

The modeled annual averaged SST over 1993–2014 basically reproduces a similar pattern to that observed (Figure 1). The isotherm of SST is basically independent of longitude, with warmest waters in the tropical ocean and coldest waters near the poles, especially in parallel with latitudes south of 40°S. The model shows warm biases in coastal regions and in the tropical eastern Pacific and Atlantic oceans. The warm biases are possibly caused by weak upwelling associated with uncertainty in the atmospheric forcing fields. Both warm and cold biases are present in the Kuroshio Extension, the Gulf Stream, the East Australian Current in southeastern Australia, the Brazil–Malvinas Confluence in the southwestern Atlantic, and the Antarctic Circumpolar Current and Agulhas Current. Such biases are common for most ocean models because of the complex physical processes at work in these regions. Near the poles the model has cold biases, which are associated with a lack of sea ice. Overall, the modeled SST has a warm bias of 0.29°C for the global ocean, a warm bias of 0.57°C for the tropical ocean (30°S–30°N), a warm bias of 0.26°C for the subtropical ocean (30°N–60°N/S), and a cold bias of 0.2°C for the North Pole (60°–90°N).

The zonally averaged SST seasonal cycle from the model and observations, along with their difference, is shown in Figure 2. Both the model and observational fields are averaged over the period 1993–2014. The modeled seasonal cycle demonstrates a similar
pattern to the observed. The SST is highest around the equator and decreases towards the poles. The isotherm moves north and south with the season, which is associated with the meridional change in solar radiation. The isotherm moves furthest north (south) in summer (winter). The seasonal cycle in the model is a little strong compared with the observations, probably because of the air–sea flux, which is something we intend to investigate in future work. In the midlatitudes of each hemisphere, except for 40°–50°N, the zonally averaged SST is 0.2°–0.4°C colder than observed in winter, and 0.2°–0.8°C warmer in summer. In the zonal band of 40°–50°N, the modeled SST is higher than observed in all seasons, which is associated with uncertainty in the simulation of the Kuroshio Extension and the Gulf Stream due to the horizontal resolution, topography, horizontal viscosity, and surface forcing, among other factors (Figure 1). The modeled time-averaged, zonally averaged SST is basically within 0.6°C of observations for most latitudes except the Gulf Stream region and the Arctic. In the polar region, the relatively large errors are mainly caused by the lack of sea ice.

### 3.2 Subsurface temperature and salinity

To provide a broad overview of the modeled large-scale ocean states, we present the climatological zonally and meridionally averaged temperature and salinity, as well as their corresponding WOA13 results.

Compared with WOA13 (Figure 3(b)), the time- and zonally averaged modeled temperature (Figure 3(a)) shows generally reasonable characteristics, with warm waters in the upper layer at low latitudes and cold waters at all depths at high latitudes. The structure of the modeled thermocline is consistent with WOA13. The difference (Figure 3(c)) shows the model has a cold bias of 0.21°C averaged over the upper 1000 m of the global ocean, which is primarily from a large cold bias of 0.84°C in the polar region (60°N–90°N/S). This indicates the importance of sea ice. The time- and zonally averaged modeled salinity (Figure 3(d) and (e)) are reproduced well, including
fresh water spreading down to about 1000 m between 60°S and 10°S corresponding to the Antarctic Intermediate water, high-salinity water related to the Mediterranean Sea sinking to about 700 m at 35°N, a high-salinity water tongue propagating downward in the subtropical surface in each hemisphere, low-salinity water associated with abundant precipitation in the ITCZ, and low-salinity water north of 50°N owing to the melting of Arctic ice. The modeled salinity is relatively fresh in the high-salinity regions (Figure 3(f)), which is probably associated with the surface freshwater flux. Overall, the model has a fresh bias of 0.16 PSU averaged over the upper 1000 m of the global ocean. Moreover, for different regions, the time and zonal mean of the modeled salinity also presents fresh biases. The fresh bias is 0.14 PSU in the tropical ocean (30°S–30°N), 0.06 PSU in the subtropical ocean (30°N/5–60°N/S), and 0.32 PSU in the polar region (60°N/5–90°N/S).

For the time and meridional mean of temperature (Figure 3(g) and (h)), the model is capable of representing the vertical structure of temperature, with warm waters in the upper ocean at almost all longitudes, with cold water related to the lack of a tropical ocean at 15°–35°E, and with warm waters related to the Gulf Stream penetrating to about 700 m at 75°–55°W. The difference (Figure 3(i)) shows the model has a temperature bias less than 1°C over most longitude–depth sections. The temperature bias averaged over the longitude–depth panel is 0.03°C. The large temperature biases at 50°–30°W are possibly associated with the vertical layers and mixing. The poles also contribute greatly to the cold biases. A similar reason is applicable to the salinity biases. For the time and meridional mean of salinity (Figure 3(j) and (k)), the model can describe realistic features, with lowest-salinity waters in the Pacific Ocean, relatively high-salinity waters in the Indian Ocean, and highest-salinity waters in the Atlantic Ocean. The modeled high-salinity waters are lower than in WOA13, especially in the Atlantic Ocean. The high-salinity waters at 70°–0°W are partly associated with the Gulf Stream, while they are associated with the Mediterranean Sea at 0°–30°E. The modeled salinity has a bias less than 0.15 PSU over most longitude–depth sections (Figure 3(l)).
salinity bias averaged over the longitude–depth panel is −0.08 PSU.

3.3 Sla

In this section, we compare the root-mean-square error (RMSE) of the modeled SLA with the altimetry data from AVISO over the period 1993–2014 (Figure 4). The modeled SLA is referenced to the model mean sea level averaged over 1993–2012. The observed SLA from AVISO is obtained using the same reference period.

In terms of the regions with local SLA maxima, the model and observations are generally consistent. Both show high SLA variability along the path of the Antarctic Circumpolar Current and Agulhas current. The high SLA variability can be observed in the model and observations in the West Boundary Current regions, including the Kuroshio Extension, the Gulf Stream Extension, the East Australian Current in southeastern Australia, and the Brazil–Malvinas Confluence in the southwestern Atlantic.

Overall, the locations of the local SLA variability maximum in the model agree with those in the observations. However, the magnitude of the modeled SLA variability at the maximum is less than that observed. The high SLA variability is related to the paths of currents, high abundance of eddies, and West Boundary Current transitions between meandering phases, which are dependent on the model resolution and its ability to accurately represent the physical processes involved. The indication, therefore, is that to accurately reproduce these phenomena, further improvement is needed in the model configurations (e.g. the parameterization schemes representing sub-grid-scale processes, the resolution, forcing fields, and so on).

3.4 Zonal current in the equatorial pacific

The Equatorial Undercurrent (EUC) centered on the equator and flowing eastward within the thermocline is an important part of the equatorial circulation system and plays an important role in the exchange of water between the tropical and subtropical regions, as well as between the Northern and Southern hemispheres. Therefore, the EUC is also a factor that should be evaluated when judging the performance of the model.

Figure 5 shows the zonal current along the equatorial Pacific. The model, observations and reanalysis show an eastward subsurface current tilting from west to east along the thermocline. It is clear that the modeled EUC is much stronger than that of ECCO, with the maximum greater than 70 cm s⁻¹. Although the EUC in the model is about 20% weaker than observed, it is still a reasonable result for an eddy-permitting ocean model. Additionally, the model can reproduce the main large-scale current systems in the global ocean, including the Kuroshio Extension, the Gulf Stream, the Antarctic Circumpolar Current, the equatorial currents, and so on (figure not shown).

4. Conclusions

This study evaluates the performance of a new global-scale, eddy-permitting ocean general circulation model with vertical hybrid coordinates against observations, based on a historical run. The SST seasonal cycle in the model is basically in good agreement with the observations, albeit a little strong in the midlatitudes. The modeled SST shows a similar pattern to the observed and has a warm bias of 0.29°C for the global ocean. The climatological zonal and meridional average of temperature and salinity shows a reasonable broad-scale ocean-state estimate. Comparison between the RMSE of the SLA from the model and observations indicates the model variability is reasonable, with the model reproducing most of the local maxima in the corresponding observational areas. Besides, the EUC of the model is much closer to that in TAO than ECCO. In general, the model results are basically realistic when compared to observations, as well as ECCO, despite some model biases, and is therefore suitable for further analyses seeking to better understand the dynamics and thermodynamics of upper-ocean states.
Some further developments are being undertaken, such as enhancing the (eddy-resolving) resolution, coupling with a sea-ice model, and so on. We expect the shortcomings recognized in this study to help with further improving the performance of the model.

Acknowledgments

The work was carried out at the National Supercomputer Center in Tianjin, and the calculations were performed on Tian He-1.

Disclosure statement

No potential conflict of interest was reported by the authors.

Funding

This work was supported by the National Key R&D Program of China [Grant No. 2016YFC1401705], the National Natural Science Foundation of China [Grant Nos. 41176015 and 41776041], the Chinese Academy Sciences Project ‘Western Pacific Ocean System: Structure, Dynamics and Consequences’ [Grant No. XDA11010203], confidential military project [Grant No. 315030401], and the State Key Laboratory of Tropical Oceanography, South China Sea Institute of Oceanology, Chinese Academy of Sciences [Project No. LTO1501].

References

Barnard, S., B. Barnier, A. Beckmann, C. W. Böning, M. Coulibaly, D. A. De Cuevas, J. Dengg, et al. 1997. “Dynamics of North Atlantic Models: Simulation and Assimilation with Resolution Models.” Christian-Albrechts-Universität Institut für Meereskunde, Kiel, Germany. 334. doi:10.3289/ifm_ber_294.

Bertino, L., K. A. Liasæter, and S. Scient. 2008. “The TOPAZ Monitoring and Prediction System for the Atlantic and Arctic Oceans.” Journal of Operational Oceanography 1 (2): 15–18. doi:10.1080/1755876X.2008.11020098.

Bleck, R. 2002. “An Oceanic General Circulation Model Framed in Hybrid isopycnic-Cartesian Coordinates.” Ocean Modelling 4 (1): 55–88. doi:10.1016/S1463-5003(01)00012-9.

Chassignet, E. P., H. E. Hurlburt, E. J. Metzger, O. M. Smedstad, J. Cummings, G. R. Halliwell, R. Bleck, et al. 2009. “U.S. GODAE: Global Ocean Prediction with the HYbrid Coordinate Ocean Model (HYCOM).” Oceanography 22 (2): 64–75. doi:10.5670/oceanog.2009.

Curry, J. A., A. Bentamy, M. A. Bourassa, D. Bourras, E. F. Bradley, M. Brunke, S. Castro, et al. 2015. “Seaflux.” Bulletin of the American Meteorological Society 85 (3): 409–424. doi:10.1175/BAMS-85-3-409.

Dee, D. P., S. M. Uppala, A. J. Simmons, P. Berrisford, P. Poli, S. Kobayashi, U. Andrae, et al. 2011. “The ERA-Interim Reanalysis: Configuration and Performance of the Data Assimilation System.” Quarterly Journal of the Royal Meteorological Society 137:553–597. doi:10.1002/qj.828.

Drange, H., and K. Simonsen. 1996. “Formulation of Air-Sea Fluxes in the ESOP2 Version of MICOM.” Technical Report 125, pp 23. Nansen Environmental and Remote Sensing Center, Norway, Bergen.

Ducet, N., P. Y. Tranon, and G. Reverdin. 2000. “Global High-Resolution Mapping of Ocean Circulation from TOPEX/POSEIDON and ERS-1 And-2.” Journal of Geophysical Research-Oceans 105: 19477–19498. doi:10.1029/2000JC900063.

Jansen, M. F., I. M. Held, A. Adcroft, and R. Hallberg. 2015. “Energy Budget-Based Backscatter in an Eddy Permitting Primitive Equation Model.” Ocean Modelling 94: 15–26. doi:10.1016/j.ocemod.2015.07.015.

Kara, A. B., E. J. Metzger, H. E. Hurlburt, A. J. Wallcraft, and E. P. Chassignet. 2008. “Multistatistics Metric Evaluation of Ocean General Circulation Model Sea Surface Temperature:
Application to 0.08 Degree Pacific Hybrid Coordinate Ocean Model Simulations.” *Arthritis & Rheumatology* 113 (C12): 16. doi:10.1002/ar.2404878.

Kuroda, Y. 2002. “TRITON, Present Status and Future Plan. Report for the International Workshop for Review of the Tropical Moored Buoy Network.” JAMSTEC, Yokosuka, Japan, 77 Pp. doi:10.1029/2008JC004878.

Lai, C. C. A., W. Qian, and S. M. Glenn. 1994. “Data Assimilation and Model Evaluation Experiment Datasets.” *Bulletin of the American Meteorological Society* 75(5): 793–809. DAAMEE>2.0.CO;2. doi:10.1175/1520-0477(1994)075<0793:.

Large, W. G., J. C. McWilliams, and S. C. Doney. 1994. “Oceanic Vertical Mixing: A Review and a Model with a Nonlocal Boundary Layer Parameterization.” *Reviews of Geophysics* 32: 363–403. doi:10.1029/94RG01872.

McPhaden, M. J., A. J. Busalacchi, R. Cheney, J. Donguy, K. S. Gage, D. Halpern, M. Ji, et al. 1998. “The Tropical Ocean-Global Atmosphere Observing System. A Decade of Progress.” *Journal of Geophysical Research* 103:14169–14240.

Metzger, E. J., H. E. Hurlburt, X. Xu, J. F. Shriver, A. L. Gordon, J. Sprintall, R. D. Susanto, and H. M. Van Aken. 2010. “Simulated and Observed Circulation in the Indonesian Seas: 1/12° Global HYCOM and the INSTANT Observations.” *Dynamics of Atmospheres and Oceans* 50 (2): 275–300. doi:10.1016/j.dynatmoce.2010.04.002.

Metzger, E. J., O. M. Smedstad, P. G. Thoppil, H. E. Hurlburt, J. A. Cummings, A. J. Wallcraft, L. Zamudio, et al. 2014. “US Navy Operational Global Ocean and Arctic Ice Prediction Systems.” *Oceanography* 27 (3): 32–43. doi:10.5670/oceanog.2014.66.

NOAA, 1988. “Data Announcement 88-MGG-02, Digital Relief of the Surface of the Earth.” NOAA, National Geophysical Data Center, Boulder, CO, U.S.A. doi:10.3168/jds.50022-0302(88)79586-7.

Persechino, A., R. Marsh, B. Sinha, A. Megann, A. Blaker, and A. New. 2012. “Decadal-Timescale Changes of the Atlantic Overturning Circulation and Climate in a Coupled Climate Model with a Hybrid-Coordinate Ocean Component.” *Climate Dynamics* 39 (3–4): 1021–1042. doi:10.1007/s00382-012-1432-y.

Rattan, S., P. G. Myers, A. M. Treguier, S. Theetten, A. Biastoch, and C. Bönig. 2010. “Towards an Understanding of Labrador Sea Salinity Drift in Eddy-Permitting Simulations.” *Ocean Modelling* 35 (1–2): 77–88. doi:10.1016/j.ocemod.2010.06.007.

Reynolds, R. W., T. M. Smith, C. Y. Liu, D. B. Chelton, K. S. Casey, and M. G. Schlax. 2007. “Daily High-Resolution-Blended Analyses for Sea Surface Temperature.” *Journal of Climate* 20: 5473–5496. doi:10.1175/2007JCLI1824.1.

Sakov, P., F. Counillon, L. Bertino, K. A. Lisæt, P. R. Oke, and A. Korablev. 2012. “TOPAZ4: An Ocean-Sea Ice Data Assimilation System for the North Atlantic and Arctic.” *Ocean Science* 8 (4): 633. doi:10.5194/os-8-633-2012.

Steele, M., R. Morley, and W. Ermold. 2001. “PHC: A Global Ocean Hydrography with A High-Quality Arctic Ocean.” *Journal of Climate* 14(9): 2079–2087. PAGOHW>2.0.CO;2. doi:10.1175/1520-0442(2001)014<2079:.

Wan, L., J. Zhu, and L. Bertino. 2008. “Initial Ensemble Generation and Validation for Ocean Data Assimilation Using HYCOM in the Pacific.” *Ocean Dynamics* 58: 81–99. doi:10.1007/s10236-008-0133-x.

Woloszyn, M., M. Mazlof, and T. Ito. 2011. “Testing an Eddy-Permitting Model of the Southern Ocean Carbon Cycle against Observations.” *Ocean Modelling* 39 (1–2): 170–182. doi:10.1016/j.ocemod.2010.12.004.

Wunsch, C., P. Heimbach, M. P. Rui, and I. Fukumori. 2009. “The Global General Circulation of the Ocean Estimated by the Ecco-Consortium.” *Oceanography* 22 (2): 88–103. doi:10.5670/oceanog.2009.41.