

Using altimeter measurements for quantitative assessment of high resolution ocean models

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ABSTRACT

With the long altimetric record and the increase in computational power and subsequent improvement in realism of ocean models, quantitative assessment of ocean models has become possible. The realism of western boundary current extensions in the highest resolution ocean models in particular has improved. To determine how well these high resolution ocean models are doing in representing western boundary currents dynamics and thermodynamics, a high resolution (0.08° at the equator) HYbrid Coordinate Ocean Model (HYCOM) simulation is evaluated against observations for the period 1993-2003 for a study region containing the Kuroshio Extension (KE) in the western Pacific ($25\text{-}45^\circ\text{N}$ and $135^\circ\text{-}180^\circ\text{E}$). Comparisons are made for the KE path and strength (measured by the SSH, sea surface height, difference), and the upper ocean heat budget. The mean strength and path agree well with observations, except near the KE separation point, where the jet is as much as 2° of latitude too far south, causing localized small SST (sea surface temperature) errors. A small (about 0.5°C) mean SST bias, too high in the northwestern part of the study region and too low in the southeastern part, remains after adjustment by the heat flux boundary condition. Long-period (about 10-yr) variations of the KE path and strength, as well as in heat content, do not match the observed variations. The upper ocean heat budget shows a strong contribution from advection in the model, similar to a diagnostic heat budget inferred from observations; however, interannual variations in advection are much larger in the model and are not correlated with those observed.

1. INTRODUCTION

Satellite altimeter missions since the 1990s have provided an important benchmark for the evaluation of the fidelity of ocean models. Eddy kinetic energy and sea surface height variability have been used extensively as a comparison point for models of northern hemisphere western boundary currents and their extensions. As longer time series of altimetry observations have become available, they can be used, along with other observations, to evaluate the model's ability to reproduce longer term variability in a quantitative way. During the 1990s, ocean models have improved immensely, benefiting from improved forcing fields, as well as from an increase in computational power. These developments have resulted in increased model resolution with an increase in realism of western boundary currents. Comparisons that are possible with the long time series of altimetric observations include an evaluation of the mean path strength of the current and

now, and path variability. In addition, the upper ocean heat budget can be examined using a diagnostic model results that rely on the altimeter observations (Vivier et al, 2002; Dong and Kelly, 2004). Hindcast model runs over some of the same time period can be evaluated against these metrics. Here, we evaluate a very high resolution model run in the North Pacific against the altimeter observations. The model run has a western boundary current that has a good separation latitude, penetration into the interior and strength. However, with a more quantitative analysis, model biases appear that can be used to infer deficiencies in model physics and forcing fields.

2. MODEL AND DATA

The model used in this study is the HYbrid Coordinate Ocean Model (HYCOM, Bleck 2002) covering the Pacific Ocean from 20°S to 66°N . The horizontal grid resolution is 0.08° in longitude by $0.08^\circ\cos(\text{latitude})$ in latitude. It has 20 vertical coordinate surfaces that are typically isopycnal in the open, stratified ocean, but make a dynamically smooth transition to z-level coordinates in the mixed layer. Closed boundaries are used for the Indonesian Throughflow region, in the Bering Strait and at 20°S . Along the southern boundary, temperature and salinity are relaxed to three-dimensional monthly climatological data. After integrating 20 model years with climatological forcing, the simulation was extended using the 6-hourly 1979-1993 ERA15 Reanalysis and then 1994--2003 ECMWF Operational forcing. Thermal forcing includes air temperature, specific humidity and radiative (shortwave and longwave) fluxes. Precipitation is also used as a surface forcing. Surface latent and sensible heat fluxes are calculated using bulk formulae given the above atmospheric variables and model SST. All model output used in this study are monthly averages from the last 11 years of the integration (1993--2003).

The AVISO product (Archiving, Validation and Interpretation of Satellite Oceanographic data), which includes TOPEX/Poseidon, Jason-1, and other altimeters was used in comparisons. The gridded product is available on a $1/3$ -degree grid at weekly intervals beginning in November 1992. Techniques to remove the earth's geoid generally also remove the mean SSH in the altimeter measurement; therefore, to get absolute SSH fields, it is necessary to add an estimate of mean SSH to the anomalies. Here we have used an estimate developed from hydrographic measurements by Teague et al (1990). The ocean model also produces a measure of SSH, which includes the mean.

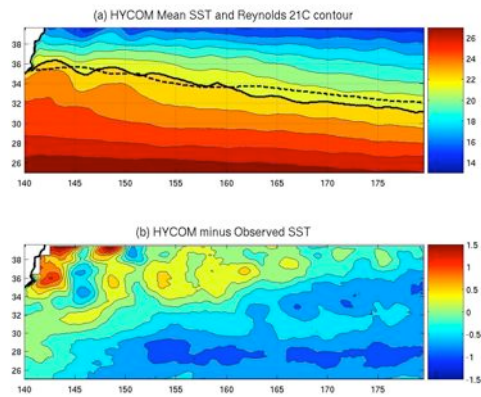


Figure 1. Comparisons of observed and modeled SST. (a) Mean of model SST and (b) model SST minus observed SST (Reynolds product). The location of the 21°C isotherm is shown in (a) for the model (solid) and the observations (dashed).

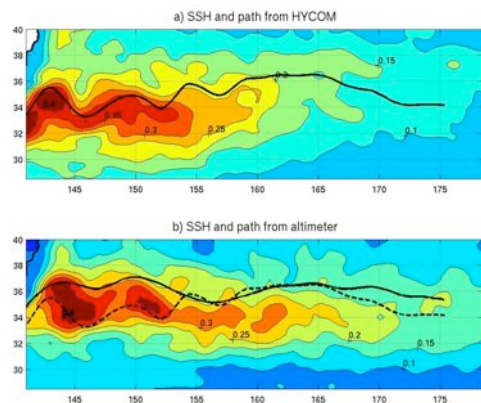


Figure 2. Mean path (bold line) from (a) HYCOM and from (b) the mean dynamic height from Teague et al (1990). HYCOM mean path is repeated in (b) as a dashed line for comparison. Paths overlaid on standard deviation of SSH from (a) HYCOM and (b) altimeter data for 1993-2003. Contour intervals are 0.05m.

3. RESULTS

In comparisons of temperature, the location of the 21°C isotherm is used as a comparison point for the fields (Fig. 1a): the model and observations agree well in the upstream region (west of 160°E), but the model's 21°C isotherm is about 1° too far south in the downstream region (east of 160°E). Accordingly, mean SST from the model (Fig. 1b) is lower than in the observed fields in the southeastern part of the region (east of 160° and south of 33°N) by about 0.5°C. In the northwestern region (west of 160°E and north of 33°N), it is higher by 0.5°C. A comparison of the variability of SSH (Fig. 2) shows similar values for the altimeter and the model, with differences primarily in the zonal extent and latitude of the high values. For example, in the HYCOM variability (Fig. 2a) the 0.15m contour stops at about 170°E, whereas in the altimeter variability

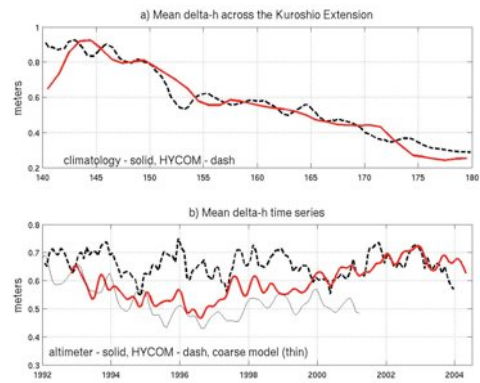


Figure 3. Model and observed mean surface current strength. (a) Temporally averaged SSH difference across the Kuroshio Extension for climatology (solid) and HYCOM (dash). (b) Spatially averaged SSH difference for altimeter (bold) and HYCOM (dash). The SSH difference time series from a 1° resolution ocean model (thin line) is shown in (b).

(Fig. 2b) the 0.15m contour extends beyond the eastern boundary of the study region; this weaker zonal penetration is fairly typical of ocean circulation models. In addition, in the model the region of highest values (west of 155°E) occurs about 2° south of the highest values in the altimeter data, suggesting that the model's jet separates somewhat too far to the south.

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As a way to make the SSH comparisons between the model and observations of the KE more specific, we introduce a simple way to quantify the path and strength of the KE by fitting the SSH to an error function. We fix the scale width to be 0.5° of latitude, and allow only the center location and its amplitude to vary. This model was applied to both the model and the observed SSH (Fig. 3). There is good path agreement when compared to low-resolution ocean models in which the western boundary current systematically overshoots the observed separation latitude. The SSH difference across the jet, is a measure of the intensity of the surface geostrophic transport, equivalent to spatially integrating

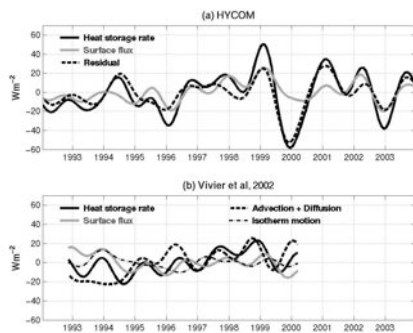


Figure 4. Vertically integrated heat budgets. Spatially averaged terms of the vertically integrated heat budget (a) from HYCOM and (b) from Vivier et al. (2002). Advection, diffusion, and isotherm motion were combined into a single term (residual) in (a). Seasonal variations have been removed and terms have been filtered to reduce variations with periods shorter than one year.

the current along a meridian. Overall, the mean surface current strength from HYCOM agrees well with the hydrographically based estimate. However, a time series of SSH difference are not significantly correlated between model and observations (Fig. 3b). A visual inspection suggests that the observed SSH difference has some long-period variations (weak jet in 1994-1997, strong jet in 1993 and again in 2000-2003) that are not reproduced by HYCOM. Differences in the jet strength anomalies between HYCOM and the observations are more pronounced upstream of 150°E ; eliminating the values upstream of 146°E from the zonal average produces a significant correlation with the altimeter. The long-period fluctuations seen in the altimeter SSH, which are presumably related to changes in the wind-forced circulation of the ocean, are generally reproduced well by low-resolution models. For comparison, a 1° isopycnal model (Hallberg Isopycnal Model, see Ladd and Thompson, 2002, for model description) was used. In the low-resolution model, we see a drop in jet strength in the early 1990s, followed by an increase in the late 1990s, similar to the long-period variations in jet strength from the altimeter; in fact, the jet strength anomalies from the low-resolution model are significantly correlated with those from the altimeter for the overlapping time period. Eddies are not resolved in the low-resolution model, and thus, changes in the circulation owing to changes in eddies or eddy fluxes are not represented. The long-period variations in current strength are mirrored by changes in the KE paths: the KE path tends to be more coherent during periods of high strength (not shown). To quantify this relationship we computed two statistics by seasons: the standard deviation of the path latitude and mean SSH difference averaged zonally over the region west of 155°E . To obtain more reliable estimates of the standard deviation of path, we used overlapping six-month periods for each quarterly estimate. Despite the

short time series, a significant negative correlation (0.84 compared with a 95% confidence level of 0.4) was obtained for the altimeter; that is, stronger surface transport is correlated with a more coherent path. The HYCOM transport-path correlation was also negative (~ 0.36 , compared with a 95% confidence level of 0.3), but was only marginally significant. Despite a similar relationship between KE strength and path coherence, neither the path coherence nor the SSH difference are significantly correlated between the altimeter and HYCOM.

To investigate the discrepancies in long-period SSH variations, we compare the relative sizes of the terms in the upper ocean heat budget (the vertically integrated temperature budget). The heat storage rate down to a fixed depth is balanced by surface heating, the divergence of heat transport, and diffusion. The HYCOM heat budget shown here (Fig. 4a) consists of three terms, the heat storage rate, the surface flux, and a residual that combines the remaining term (all to a depth of 400 m). These same terms could be estimated directly from the observations, assuming that SSH represents heat content, but the residual would lump all sources of error together with the lateral fluxes (advection and diffusion). However, a heat budget for this region, which does close, was computed by combining horizontal velocities derived from observations and surface fluxes with a simple model of upper ocean temperature. This study (Vivier et al, 2002) produced estimates of the terms in (5) in a time period that overlaps the period of this evaluation. The study showed that most of the changes in SSH can be explained by changes in the ocean heat content in the upper 400 meters and that, for interannual time scales, the advection of heat into the KE region is at least as important in creating heat content anomalies as are air-sea fluxes (Fig. 4b). Consistent with this analysis, the heat budget from HYCOM (Fig. 4a) shows that advection and diffusion are primarily responsible for interannual variations in upper ocean heat content. However, both the heat content anomalies and the advection-diffusion terms in HYCOM are considerably larger. The peak fluctuations in HYCOM heat storage have little correspondence with either observed SSH or the heat content variations computed from the heat budget of Vivier et al (2002) (Fig. 4b), which reproduced well the observed long-period SSH variations.

4. CONCLUSIONS

HYCOM represents a substantial improvement over low-resolution models in reproducing characteristics of the Kuroshio Extension region and there is considerable agreement between model and observations, particularly in the mean. Although assimilated observations would likely correct many model biases, the performance of high resolution models without

assimilation is of great interest to the oceanographic community for use in predictions at seasonal and longer time scales. The time-varying differences between HYCOM and observed SSH and SST suggest directions for further investigation of the model results, particularly for periods of 10 years or longer. SSH was used to evaluate HYCOM, as a proxy for heat content; a comparison between the altimetric and HYCOM SSH anomalies again showed problems in the long-period behavior of HYCOM. However, estimates of the contributions of air-sea fluxes to SSH suggested that surface fluxes are too small to be the primary source of the discrepancy. The heat budget analyses give complementary information about HYCOM performance. Lateral fluxes dominate the contributions to interannual variations in heat storage rate, as was found in previous observationally based estimates (Fig. 4). The large contributions of advection in HYCOM are made possible by the energetic currents of the high-resolution model. However, the contributions from the lateral fluxes and the resulting variations in heat storage rate are substantially larger and at higher frequencies than was found by Vivier et al (2002). It is possible that these large variations are associated with the changes in the path or in the path stability. The sources of the discrepancies in longer-period (10 years) behavior in HYCOM are difficult to determine, but the ability of a low-resolution model to simulate the observed wind-forced long-period variations in current strength may be a clue: the addition of more eddy variability may be obscuring the large-scale wind-forced response. This hypothesis is supported by the low stability of the KE path compared with observations and indicating that the KE model jet is too turbulent.

It is unclear whether a model of this type coupled to a

high-resolution atmosphere would show the same biases, but it does suggest that a critical look at the processes that control eddies and drive the recirculation gyre must be examined in any high-resolution simulation. From this relatively short period, it is difficult to assess the net effects of model biases (such as KE path stability) in heat content variations, air-sea fluxes, and ocean circulation, both in the mean and on decadal time scales. Errors in the forcing fields (wind stress or atmospheric variables) used in the simulation may be a factor, such that even with perfect model physics, the simulation could be in error. We await longer term coupled simulations at high resolution to determine the effects of western boundary current variations on the climate system. The forced ocean model simulation evaluations described here are a first step in determining the validity of high resolution coupled simulations of future climate.

A new appreciation of the importance of the shallow wind-driven circulation on oceanic heat transport [13] suggests that changes in the meridional heat transport may be dominated by upper ocean western boundary current variability rather than by changes in the deep thermohaline circulation. A heat budget analysis which spans both the subtropical and subpolar gyres, along with estimates of heat transport at depth, is needed to examine this issue further. Critical to this analysis are both longer time series of altimetric SSH and an improved mean SSH over the larger region as well as an understanding of the influence of salinity and the fresh water budget. The observationally derived estimates of the thermodynamic budget of the upper ocean are essential for independently evaluating new ocean and climate models, especially for eddy resolving models.

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