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A Comparison Study of Tropical Pacific Ocean State Estimation: Low-Resolution Assimilation vs. High-Resolution Simulation

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ABSTRACT

A comparison study is performed to contrast the improvements in the tropical Pacific oceanic state of a low-resolution model respectively via data assimilation and by an increase in horizontal resolution. A low resolution model (LR) (1°lat by 2°lon) and a high-resolution model (HR) (0.5°lat by 0.5°lon) are employed for the comparison. The authors perform 20-yr numerical experiments and analyze the annual mean fields of temperature and salinity. The results indicate that the low-resolution model with data assimilation behaves better than the high-resolution model in the estimation of ocean large-scale features. From 1990 to 2000, the average of HR's RMSE (root-mean-square error) relative to independent Tropical Atmosphere Ocean project (TAO) mooring data at randomly selected points is 0.97°C compared to a RMSE of 0.56°C for LR with temperature assimilation. Moreover, the LR with data assimilation is more frugal in computation. Although there is room to improve the high-resolution model, the low-resolution model with data assimilation may be an advisable choice in achieving a more realistic large-scale state of the ocean at the limited level of information provided by the current observational system.

Key words: comparison study, high-resolution model, data assimilation, low-resolution model

1. Introduction

The main common scientific goal of ocean modeling and data assimilation is to generate as optimal estimates of the time-varying ocean state as possible, thereby enhancing the forecast accuracy. Doing this in real time requires the interplay between a variety of datasets, relatively accurate ocean circulation models and optimal data assimilation algorithms. However, high-resolution modeling and data assimilation follow different paths in pursuing such a goal.

Data assimilation is a comprehensive system that incorporates the dynamic model, observations and computation techniques, namely, a combination of observation and ocean simulation by way of mathematical methods. There have been many studies in this area over the last two decades (Derber and Rosati, 1989; Parrish and Derber, 1992; Errico et al., 1993; Courtier et al., 1998; Zhu and Kamachi, 2000). However, ocean simulations depend mainly on the oceanic circulation model itself, which includes both a complete representation of the thermodynamics process responsible for water mass formation and sufficient horizontal resolution to allow for the hydrodynamic instability responsible for eddy formation. But due to the limitation of present-day, available computational resources, the horizontal resolution is typically set to 100–200 km, and apparently, such a coarse resolution cannot resolve quasi-horizontal mesoscale eddies (with a length scale of 10 km to 100 km) or explicitly represent their bulk effect. Considerable efforts have been made to resolve problems in ocean simulations during the last 20 years. Cox (1985) used a three-dimensional, primitive equation numerical model to study the effects of mesoscale eddies within the subtropical thermocline. Bryan (1987) used a coarse resolution model to test the sensitivity of the magnitude of vertical diffusion to a model solution. Stammer and Böning (1992) investigated the meso-scale variability characteristics in the Atlantic Ocean and their comparison indicated that a high resolution model with a horizontal resolution of (1/3)°(lat) by (2/5)°(lon) in latitude and longitude is capable of simulating the eddy characteristics observed in the Tropics and subtropics. This

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model has been extended (Holland and Bryan, 1993a) from the basic (1/3)°(lat) by (2/5)°(lon) model to include the higher horizontal grid spacing (1/6)°(lat) by (1/5)°(lon). Others have also conducted many investigations and much has been learned from global- and basin-scale eddy permitting simulations with resolutions in the range of (1/2)°–(1/6)° (Chao et al., 1996; Bleck et al., 1997; Maltrud et al., 1998). Smith (2000) used a level-coordinate ocean general circulation model with a resolution of 0.1°(lat) by 0.1°(lon) to simulate the North Atlantic Ocean. Tokamakian and McClean (2003) studied the high-frequency signals in a 0.1° model of the North Atlantic. These models were able to produce many aspects of wind-driven circulations, particularly at low latitudes where the grid spacing is sufficiently small compared to the dominant scales of motion to capture the important dynamics. At the same time, we note that a coarse resolution model combined with data assimilation also generates an amendment to the model's simulations and the effect is very significant especially to the large-scale features. Consequently, the question is asked that in a given observational system, what is the difference between results of a high-resolution simulation and a coarse resolution model with data assimilation?

In this paper, we make use of a tropical Pacific model with a horizontal resolution of 2°(lat) by 1°(lon) in longitude and latitude (Zhang and Endoh, 1992) and its higher horizontal resolution (0.5°(lat) by 0.5°) (lon) version to explore such a question. The 2°(lon) by 1°(lat) model is referred to as the low-resolution model (LR) and the 0.5°(lon) by 0.5°(lat) model is considered the high-resolution model (HR). The two models' main difference lies in their horizontal resolution and horizontal eddy viscosity. The assimilation scheme used in this study is optimal interpolation (OI). Twenty-year numerical experiments are carried out based on the LR and HR, respectively. Thus, we can obtain the simulations of LR and HR. Then we perform a temperature assimilation on the LR. By comparing the results from these three experiments, we can investigate the extent of the improvement brought about by the HR and the data assimilation to determine which one is better. The emphasis in this study will be placed on the analysis of the temperature field, as it is greatly altered by the assimilation. Other interesting features found in the comparison will not be fully addressed.

Section 2 introduces the model and the assimilation scheme. In section 3, the results of the comparison are shown and studied from different aspects. A discussion and conclusion are given in section 4.

2. Description of the ocean model and assimilation scheme

2.1 *Ocean model*

The Tropical Pacific General Circulation model chosen in this study was first developed by Zhang and Endoth (1992) and is now used for SST forecasts (Zhou et al., 1999). It is a free surface model in σ coordinates. The dynamics of the model are governed by the primitive equations under hydrostatics and the Boussinesq approximation. The model domain extends from 30°N to 30°S and 121°E to 69°W and in the tropical Pacific Ocean. The model horizontal grid sizes are 1° in latitude and 2° in longitude. The flat-bottom ocean is 4000 m deep. In the vertical, σ is divided unequally into 14 layers with a 20-m resolution in the upper 60 m and a 30-m resolution between 60 m and 240 m. It is used mainly to simulate the upper tropical Pacific Ocean. The model introduces a standard stratification and contains a convective adjustment procedure when hydrostatic instability takes place. The lateral boundaries are assumed to be "non-flip" and insulation, but at the north and south boundaries the relaxation terms $\gamma(T_* - T)$ and $\gamma(S_* - S)$ are added to the $T - S$ equations, where T and S are temperature and salinity respectively, γ is the Newton cooling coefficient equal to $(60\ \mathrm{d})^{-1}$, and T^* and S^* are the climatological values of Levitus (1982).

The horizontal eddy viscosity is $2\times10^3\ \mathrm{m}^2\ \mathrm{s}^{-1}$ equatorward of 10° latitude; poleward of this, it increases linearly to $3\times10^4\ \mathrm{m}^2\ \mathrm{s}^{-1}$ at 30°N/S; the lateral eddy diffusivity of temperature and salinity is held constant at a value $2\times10^3\ \mathrm{m}^2\ \mathrm{s}^{-1}$; the vertical eddy viscosity and diffusivity are dependent on the Richardson number related to current shear and stratification (Pacanowski and Philander, 1981). Time steps for the barotropic and baroclinic modes are 5 min and 2 h respectively.

A fine resolution version is developed and examined through the annual and monthly integration experiments on the basis of the coarse resolution model. The previous model is extended from the basic 2°(lon) by 1°(lat) model to a much higher horizontal resolution of 0.5° by 0.5°, and a more realistic coastline is obtained from a real 0.5°×0.5° tropical topography. In the coarse grid case, the viscosity coefficient must be relatively large to resolve the viscous boundary layer. As resolution is increased, the viscosity and diffusivity coefficients are decreased. We take a fold-line form to calculate the eddy viscosity. The horizontal eddy viscosity is $0.5\times10^3\ \mathrm{m}^2\ \mathrm{s}^{-1}$ equatorward of 10° latitude; poleward of this, it first increases linearly to $0.5\times10^4\ \mathrm{m}^2\ \mathrm{s}^{-1}$ at 25°N/S; and then increases linearly to $0.7\times10^4\ \mathrm{m}^4\ \mathrm{s}^{-1}$ at 30.5°N/S. Vertical viscosities and diffusivities are computed using the Richardson number formulation of Pacanowski and Philander (1981) with background values of 10^{-4} and 10^{-5} $\mathrm{m^2\ s^{-1}}$. Time steps for the barotropic and baroclinic modes are 1.25 min and 0.5 h respectively.

2.2 *Data and assimilation scheme*

The data types, accuracy and their distribution play an important role in the assimilation. In this paper, we only perform temperature data assimilation using XBT (expendable bathythermograph measurement) profiles compiled by NCEP. The XBT data have undergone standard quality control to remove bad records. Some other data are also selected to drive the model. For example, the wind stress used in this study is a combination of climatological surface wind stress (Hellerman and Rosentein, 1983) and FSU (Florida State University) wind stress anomaly (Bourassa et al., 2001), the surface heat flux Q_{T} is calculated according to the Haney (1971) formation by the climatological data of Esbensen and Kushnir (1981), and the water mass flux Q_{S} is taken as the E–P (difference between evaporation and precipitation) from the data provided by Jaeger (1976). The *World Ocean Altas 1998*(WOA98) (Conkright et al., 1998) is also used for comparison with the experimental results.

The ocean data assimilation scheme is Optimal Interpolation as described in Derber and Rosati (1989). But, following Navan and Legler (1987), we adopted the conjugate gradient method to solve the cost function. In addition, the background error covariance was estimated from the model output (Fu et al., 2004). We performed the assimilation every day of the OGCM integration. Moreover, a 30-d window was selected in the assimilation so that the corrections at a given time included observations within ±15 d of that moment. Some results will be presented below.

3. Comparisons of the results

To analyze and compare the difference between results of the high-resolution model and the low-resolution model with assimilation, we perform three sets of numerical experiments from 1982 to 2001: low-resolution model simulation, high-resolution model simulation, and low-resolution model assimilation. The external forcing of the two models are based on the same set of data. The treatment of the external forcing is able to guarantee no interference to the results by the data qualities, that is to say, all the data in the three experiments are obtained from the same observation system. Some results from the LR, HR, and LR with temperature assimilation are presented in this section.

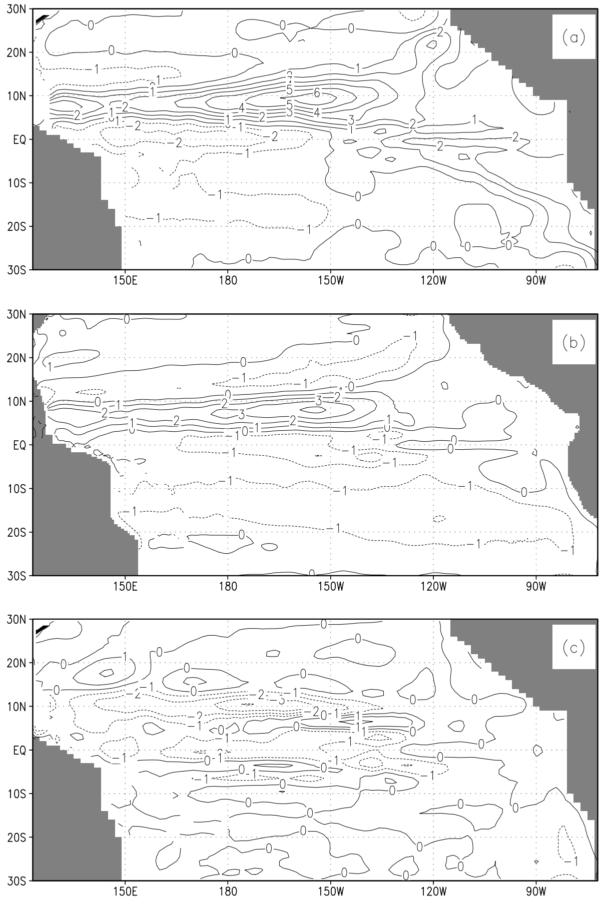

Fig. 1. Difference of annual mean temperature at the depth of 135 m, for (a) LR simulation minus WOA98, (b) HR simulation minus WOA98 and (c) LR assimilation minus WOA98. (Contour interval is 1°C.)

The raising of the horizontal resolution enables the model to incorporate small-scale structures and reflect more detailed spatial changes. First, we will examine the difference in temperature between the LR simulation, HR simulation, and LR assimilation and WOA98 analysis data at a certain level. The distribution of the difference of subsurface temperature at the depth of 135 m is given in Fig. 1. We can clearly see that between 10°N and 10°S the simulation of HR is closer to the WOA98 analysis data than that of LR. The 6°C difference centered at (7°N, 145°W) in the North Pacific is greatly reduced to about 3°C, and in the western equatorial Pacific the difference in temperature is also decreased to 1°C or lower. From Fig. 1c, we can see that after the assimilation the temperature in the central Pacific north of the equator is over-adjusted, the biggest difference is about −3°C, which is negative

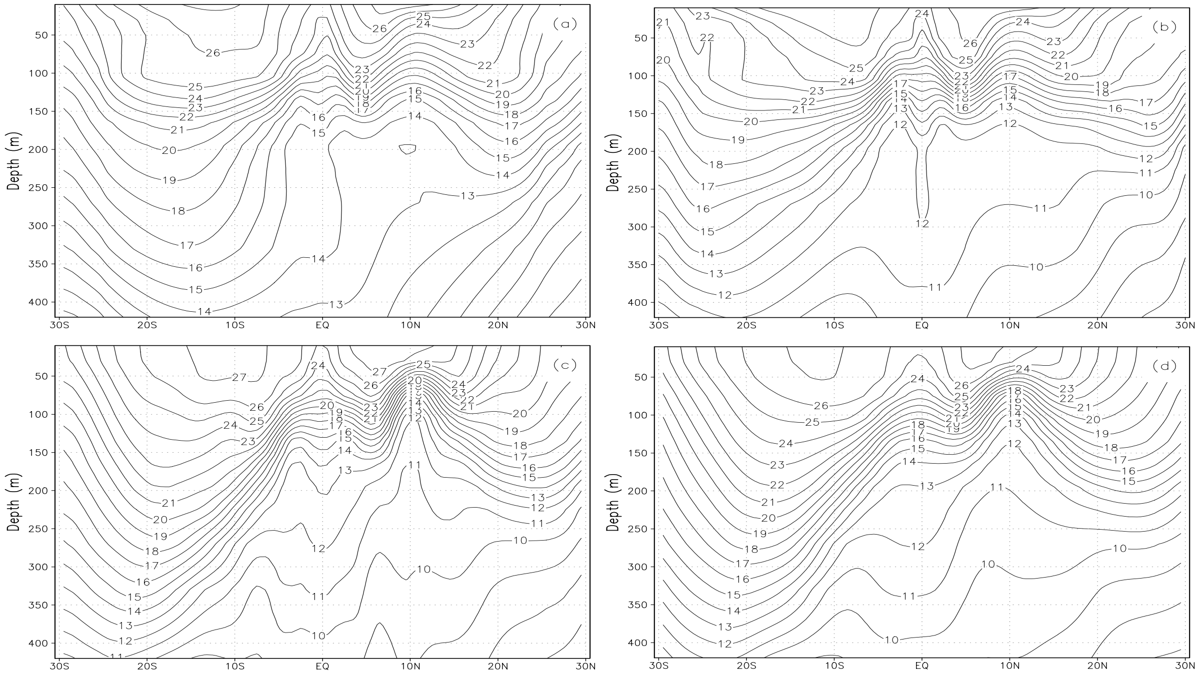

Fig. 2. Cross section of annual mean temperature along 130°W for (a) LR simulation, (b) HR simulation, (c) LR assimilation, and (d) analysis data from WOA98. (Contour interval is 1°C.)

instead of positive as in the LR and HR simulations. But in the areas near 20°S, the simulation of HR presents a difference of about 2°C, and the difference is larger than that of LR's simulation and LR's assimilation. Generally speaking, the simulation of HR and LR's assimilation are obviously better than the corresponding results of LR between 10°N–10°S, but the difference in temperature still exits in both the simulation of HR and LR's assimilation even with some improvement. But as a whole, of the three experiments, the result of LR with assimilation is closest to the analysis data. Not only does it show a smaller difference from the analysis data and produces and gives a better approximation of the main features.

In Fig. 2, the latitude-depth profile of annual mean temperature along 130°W is shown. Compared with WOA98 data, the result of LR shows several biases. The most apparent biases are the sparse isolines in themocline, the considerably higher temperature below the thermocline from north to south, and the improperly curved ridge-line around 17°S. At 10°N, the temperature trough is weaker. In the results of HR, the higher temperature at lower levels is to some degree corrected and the trough-ridge structure is closer. However, the improvement is still not as noticeable as the result with assimilation. This may be accounted for by the coarse resolution in the vertical direction. Figure 3 displays the east-west cross section of annual mean equatorial temperature. The feature of the tropical Pacific is that there is a seasonal, westward-tilted thermocline. The bias of the LR's results lies in that the gradient of the thermocline is weak and the isotherm is very sparse. Meanwhile, the temperature is higher than the analysis data at the lower layers of the ocean. The biases are amended in HR to some extent, but at the low layers, the correction is not very satisfactory. But the assimilation of LR rectifies the two biases notably. After assimilation, the isotherms are dense and the gradient of the thermocline is strengthened. The annual mean field indicates that the raising of horizontal resolution in a coarse model only brings limited improvements to the simulations, which are apparently not as remarkable as the assimilation.

To go further into the analysis of the LR assimilation and HR simulation, we choose some independent observations to make a comparison. On the diagram of the distribution of TAO (Tropical Atmosphere Ocean project) stations, we divide the domain into many 10° × 10° subdomains and make sure that at each subdomain at least one TAO mooring site is selected. To ensure that the selected TOGA/TAO real observational data are independent, we eliminated the corresponding points contained in the XBT dataset that were used to do the assimilation. Figure 4 shows the selected points of the TAO mooring data. Firstly, we calculate the average of the daily observational data at each month, and then compute the RMSE (root-

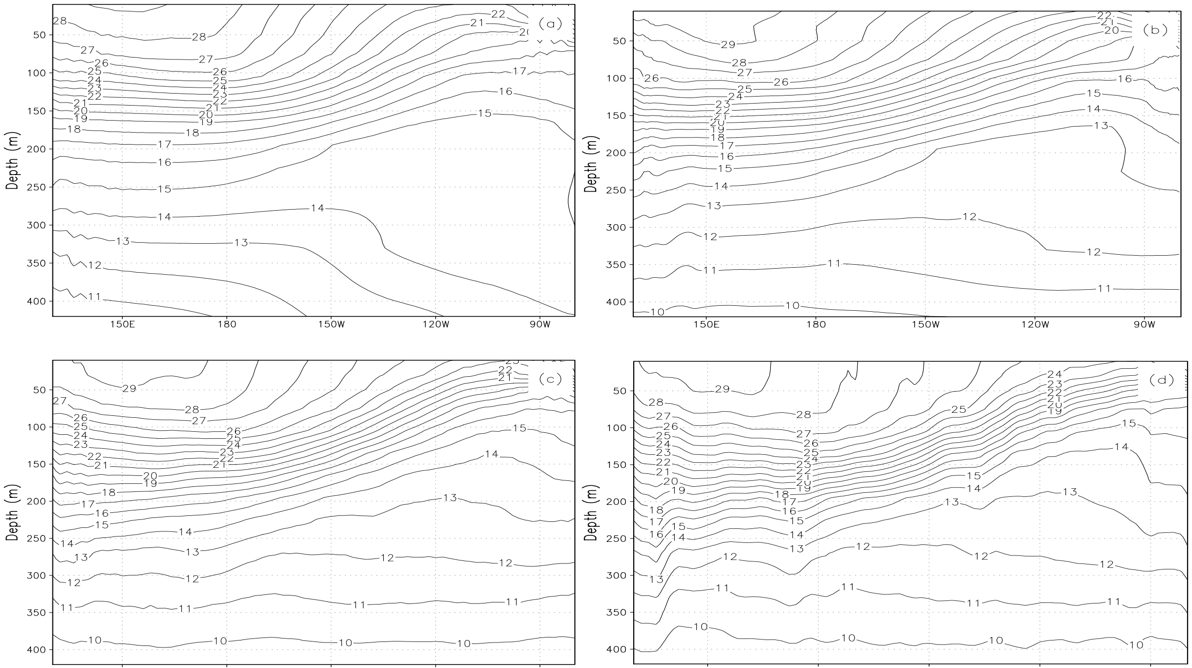

Fig. 3. As Fig. 2, along the equator.

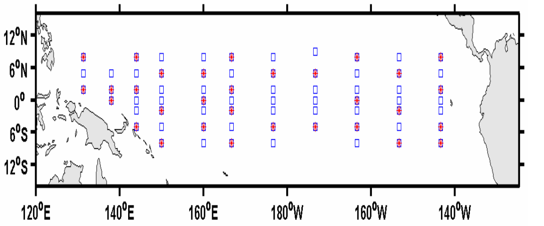

Fig. 4. Distribution of TOGA/TAO mooring data (squares). The squares with stars show the randomly selected points of TAO mooring data.

mean-square error) of the results of LR, HR and LR with assimilation relative to the selected TAO data to display a time-varying effect of HR and LR with assimilation. The result from 1990 to 2000 is presented in Fig. 5. It clearly exhibits the contrast of improvement induced by the HR and LR with assimilation. The obtained improvement is more noticeable in almost every month for LR with data assimilation than for the HR. The RMSE averages from 1990 to 2000 for LR, HR and LR with assimilation are 1.29°C, 0.97°C, and 0.56°C, respectively.

Besides the temperature field, some changes are produced in salinity and zonal velocity both in the simulation of the high-resolution model (HR) and in the results of assimilation. Figure 6 gives the distribution of the difference in annual mean surface salinity between results of LR, HR, and LR with assimilation and WOA98 analysis salinity data at the depth of 135 m.

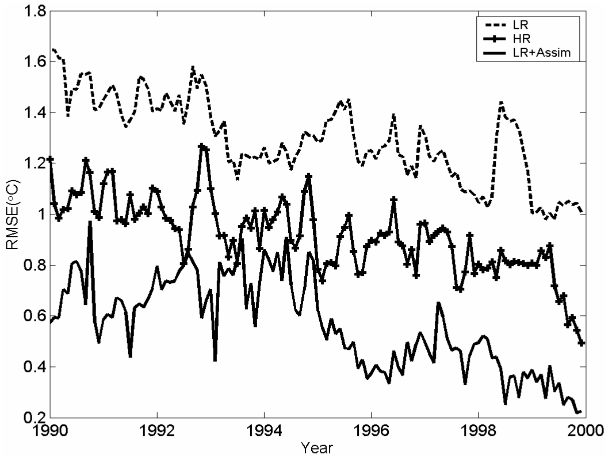

Fig. 5. The change of RMSE (root-mean-square error) at the points shown in Fig. 4 with time. The line with crosses denotes the LR simulation, the dashed line is the HR simulation, and the solid line shows the LR assimilation with temperature.

We can see that the HR behaves better than LR in the East Pacific. In the West Pacific, the difference of salinity is reduced by about 0.4 psu after the horizontal resolution is increased. But in the area of the West Pacific south of the equator, both the HR and LR with assimilation fail to produce pleasing results. The reason may be ascribed to the fact that the data used to calculate fresh water flux, namely, evaporation

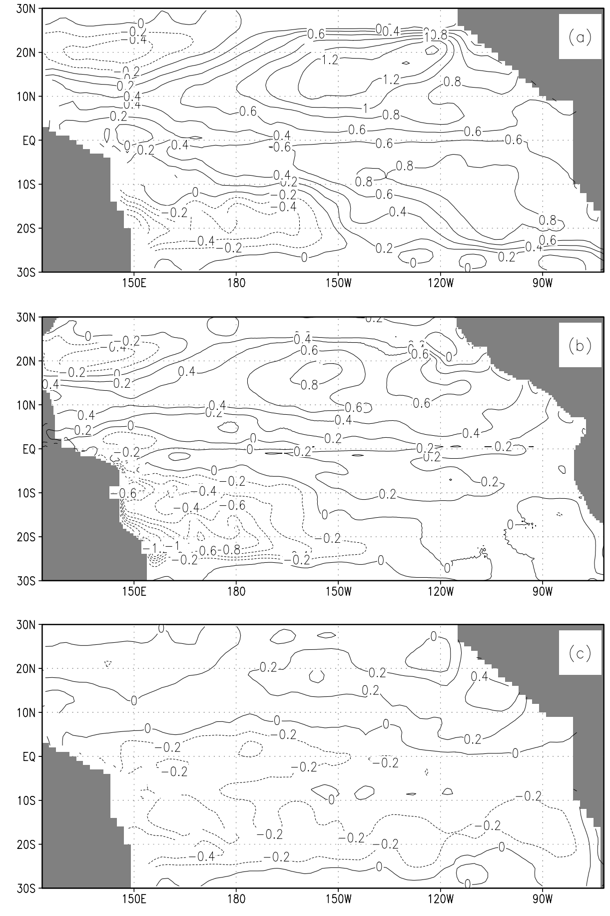

Fig. 6. As Fig. 1 for annual mean salinity. (Contour interval is 0.2 psu.)

minus precipitation (E–P), are very sparse and not so accurate in this area, and as such, could not render sufficient information. Therefore, it is easy to conceive that the forcing for salinity in fact contains great errors in these areas. The difference in the result of HR in this area is even worse than that of LR because the interpolation also brings errors to some extent. Generally, it is evident that the results of LR with assimilation are closer to the WOA98 salinity than those of HR. The difference of salinity is reduced to about 0.4 psu in almost the entire Pacific, even in the areas north of the equator.

The changes in the temperature also produce some improvement in the velocity field accordingly. The equatorial undercurrent is enhanced both in HR and LR with assimilation due to the rectification of the thermocline. The current system at the surface also improves in the simulations of HR. We do not treat this in this paper. From the above comparisons, we can draw a preliminary conclusion that the raising of horizontal resolution to the level in this study does not bring revolutionary improvements to the low-resolution simulations, and many of the large-scale features see little change although some new features appear. As far as this comparison is concerned, the LR with assimilation behaves better than the high-resolution model.

4. Conclusion

In this paper, we use a low-resolution model and a high-resolution model to examine the results between low-resolution model assimilation and high-resolution model simulation. By comparing the results, we can see clearly that the low-resolution model's assimilation is better than the outcome of the high-resolution simulations for the temperature and salinity field at least for the ocean model with a horizontal resolution of 0.5° and 0.5°. The distribution of temperature at a given layer is somewhat improved in the HR, but the effect is not as significant as in the LR with assimilation, which is more evident if a cross section is examined. Furthermore, the RMSE average from 1990 to 2000 for HR is 0.97°C compared with 0.56°C in the LR with data assimilation. To a large extent, the comparison shows the basic capacity of LR with data assimilation and of the HR for simulating the tropical ocean state. The low-resolution model with data assimilation performs better, at least for the configuration of experiments presented in this paper.

The external forcing is extracted from the same dataset, so the improvement due to the quality of observation is precluded in advance. So what accounts for the improvement in the high-resolution model is, to a great extent, attributed to the raising of the model's horizontal resolution, while the improvement assigned to the data assimilation in LR is attributed to the assimilation. Of course, one direct advantage of the high-resolution model is the better representation of the model's topography, leading to a better representation of relatively small-scale properties. But the eddy-permitting (1/2°) ocean general circulation model (OGCM) is still not sufficient to capture the bulk of the energy in the mesoscale eddy spectrum. Possibly a horizontal resolution of (1/10)° works well. Simply speaking, simulating the large-scale features does not require us to increase the horizontal resolution to that level because the assimilation performs better. In addition, the information in the current observational system is limited. Moreover, high-resolution simulation is orders of magnitude more costly in computation than the low-resolution simulation. Specifically, the amount of computation required for the high-resolution model is about 30 times that of the low-resolution model. Such a factor cannot be neglected when implementing such experiments.

Based on a certain resolution of the current observations and the data quality, what we are more concerned about is with what the ideal horizontal resolution of the ocean model should be. The optimal resolution, beyond which any enhancement in the resolution results in little improvement in the simulation, signifies a proper fitting between the model and the observations. The question regretfully remains unanswered due to the limitation of computational resources. That is to say, we cannot repeat the experiments with a variety of models each with different horizontal resolutions. But from our experiment we can draw a preliminary conclusion that, as for large-scale properties of the ocean state under the current situation of observations, the data assimilation is more advisable compared to raising the resolution to (1/2°). The ultimate goal is to achieve a more realistic state of the ocean，however, within computational limits whether to raise the model's resolution or implement data assimilation rests with oneself according to different needs. Undoubtedly, the simulations of HR have space to improve by altering the physical parameterization of the subgrid scale properties. Nevertheless, a low-resolution model (grid spacing 2° or less) with data assimilation is an advisable choice in simulating the large-scale ocean state.

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Erratum

In the paper "An Improved Method for Doppler Wind and Thermodynamic Retrievals" by Liu Shun, Qiu Chongjian, Xu Qin, Zhang Pengfei, Gao Jidong, and Shao Aimei (No. 1, Vol. 22, 90–102), the following corrections should be made.

The name of the first author should be LIU Shun. Here, the family name is capitalized.

Key words are supplemented as: Doppler radar, wind retrieval, thermodynamic retrieval, time variation.