

# Reconstruction of eddies by assimilating satellite altimeter data into Princeton Ocean Model

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## Abstract

An optimal interpolation assimilation model for satellite altimetry data is developed based on Princeton Ocean Model (POM), which is applied in a quasi-global domain, by the method of isotropic correlation between sea level anomaly (SLA) and sea temperature anomaly. The performance of this assimilation model is validated by the modeled results of SLA and the current patterns. Comparisons between modeling and satellite data show that both the magnitudes and distribution patterns of the simulated SLA are improved by assimilation. The most significant improvement is that meso-scale systems, e.g., eddies, are well reconstructed. The evolution of an eddy located in the northwest Pacific Ocean is traced by using the assimilation model. Model results show that during three months the eddy migrated southwestward for about 6 degrees before merging into the Kuroshio. The three dimensional structure of this eddy on 12 August 2001 is further analyzed. The strength of this warm, cyclonic eddy decreases with the increase of depth. The eddy shows different horizontal patterns at different layers, and the SLA and temperature fields agree with each other well. This study suggests that this kind of data assimilation is economic and reliable for eddy reconstruction, and can be used as a promising technique in further studies of ocean eddies as well as other fine circulation structures.

**Key words:** data assimilation, eddy, numerical model, optimal interpolation, POM

## 1 Introduction

Due to the lack of the knowledge of the physics of the oceanic system and the finite-differencing in a meshed system, the current numerical models provide only approximations of the actual ocean (Qiao et al., 2004). Besides, the observations of oceanic system, including measurement errors, are often irregularly distributed in space and insufficient in duration. Therefore neither numerical model nor observation alone is able to provide a realistic, temporally and spatially continuous evolution of the oceanic states.

Data assimilation combines model dynamics with observations in an optimal way to form a more realistic depiction of the ocean circulation and temperature/salinity distributions (Yin, 2004; Yin et al., 2003). Data assimilation is very important for numerical studies. On the one hand, it can provide reason-

able estimation of the initial conditions for numerical models. On the other hand, assimilation model produces high-quality, temporal and spatial continued data for the diagnoses and analyses of physical processes. With the rapid progress of numerical analysis technique and computation facilities, data assimilation has been playing a more and more important role in both operational prediction of ocean environments and theoretical researches of oceanography.

After decades of development, global ocean general circulation model (OGCM) is now capable of reproducing reasonable thermohaline fields and basic circulation patterns, which agrees well with the climatology in large scale. However, many meso-scale systems such as ocean eddies are far from been resolved by OGCMs, unless regional models with eddy-resolving meshes are employed at extremely high com-

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putational cost. As discussed by Holland and Capotondi (1996), ocean model results are highly dependent on the choice of parameterization schemes. Better parameterization, which requires sufficient understanding of the physics of eddy, including eddy generation dynamics, eddy-current interaction, etc., is indispensable for OGCM in order to reconstruct oceanic eddies at present.

In fact, data assimilation provides an economic and promising alternative for ocean eddy modeling. In a data assimilation system, as discussed above, large quantity of observations can be merged into prognostic ocean circulation numerical models. Thus even models of moderate spatial resolution, after absorbing observed data which comprise comprehensive information of multi-scales, might get the similar performance to the very high resolution ones without assimilation.

Optimal interpolation (OI) is a common technique out of various data assimilation methods. Moderate computation cost and pretty well performance stamp its most striking feature, which is extraordinarily valuable for ocean models covering large domain (such as global OGCM). For the eddy study using OI method, a key point is how to project the surface satellite data into the deep ocean (Haines, 1991; Ezer and Mellor, 1994). Without the projection, it may not be capable to constrain primitive equation models (Pinardi et al., 1995). Many projection schemes have been proposed. The projection could be based on correlation factors between the variations of surface data and those of subsurface temperature or salinity (Mellor and Ezer, 1991; Ezer and Mellor, 1994; Ezer and Mellor, 1997), the correlation between surface and subsurface pressure (De Mey and Robinson 1987), sea surface height (SSH) anomaly and potential vorticity (Holland and Malanotte-Rizzoli 1989, Alves et al., 2001), or dynamic height and the coefficients of empirical orthogonal functions of vertical temperature profile (Carnes et al., 1990). Mellor and Ezer (1991), Ezer and Mellor (1994, 1997) studied the assimilation of SSH, sea surface temperature (SST) and Expendable Bathy Thermograph (XBT) data in the north of the Atlantic Ocean. Their results showed that SST and SSH are continuously assimilated into Princeton Ocean Model (POM) with the computation cost increasing by only 10-20% compared with non-assimilation modeling. Almost all such assimilation practices were applied in regional models; as far as we know, no application in global domain has been reported.

In this study, the technique of projection, based on correlation factors between SSH anomaly and the subsurface temperature, is used to set up a numerical system to assimilate satellite-derived sea level anomaly (SLA) into a quasi-global ocean circulation model. The details of constructing the assimilation system are given in the next section. After the performance evaluation of the assimilation system in Section 3, the evolution and three dimensional structures of the reconstructed eddies are analyzed in section 4, followed by summary and conclusions.

## 2 Data and methodology

### 2.1 Data

Many satellite altimetry systems, such as TOPEX/POSEIDON, Jason, and ERS-1/2, measure sea surface height by radar altimeters with high accuracy (Wunsch and Gaposchkin, 1980; Stewart, 1985; Fu et al., 1988; Fu et al., 1996). Satellite-derived SLA contains synoptic information of ocean motions in multi-scales. In this study, the SLA derived from TP/Jason and ERS/ENVISAT is assimilated into numerical model to provide a data set of ocean which is continuous temporally and spatially. SLA data from different altimeters were merged together to increase the reliability (Ducet, 2000).

In this study, the altimeter products are produced by the Collecte Localisation Satellites (CLS) Space Oceanography Division. The data series provide a "map" every 7 days for a period of more than 11 years (from October 1992 to January 2004) on MERCATOR  $1/3^\circ$  grids.

### 2.2 Numerical model

The basic model is the cornerstone of successful assimilation practice. Data assimilation based on a reliable model can enhance the model performances, while the assimilation results from a poor model, in contrast, might become even worse. Here we use POM as the test bed for data assimilation.

POM is commonly accepted as a classic ocean circulation model. After its first development by Blumberg and Mellor in 1973, its successful application has extended from modeling of barotropic tides (Lü et al., 2007), shelf circulation (e.g., Xia, 2006; Qiao et al., 2001; Oke et al., 2002; Gan and Allen 2002), coastal upwelling (Qiao et al., 2006; Lü et al., 2006), to the general circulation study in basin and global oceans (e.g., Ezer and Mellor, 1997; Kagimoto and Yamagata, 1997; Guo, 2003; Xia et al., 2004) in the past decades.

POM has also been adopted in ocean forecast system (Oey, et al., 2005; Yin and Oey 2007). Details of POM can be found in Blumberg and Mellor (1973).

Same as Xia et al. (2004), the model domain in this study is from 78°S to 65°N. The model ocean is discretized into 15 sigma layers in the vertical, and has a horizontal resolution of 0.5° by 0.5°. Cyclic boundary condition is used in the west-east boundary, and solid boundary conditions are used for the north and south boundaries for simplicity. The topography of the model is interpolated from the global 5' by 5' Etopo5 dataset with the minimum and maximum depth set to be 10 m and 3000 m, respectively. The initial temperature and salinity are set as the Levitus annually mean values. The monthly mean sea surface heat flux and wind stress from Comprehensive Ocean-Atmosphere Data Set (Arlindo de Silva, 1994) are used as surface forcing. Similar to Fang and Wei (2002), the model was integrated for 6 years and the results of the last year are used in this study. The results were put out at an interval of 5 days.

### 2.3 Assimilation algorithm

First, some statistical coefficients should be prepared. These statistics coefficients are the matrixes of correlation factors  $F^T$ , and correlation coefficients  $C^T$  which relate SLAs to subsurface temperature anomalies, as defined by Eqs. (1) and (2).

$$F^T = \frac{\langle \delta T \delta \eta \rangle}{\langle \delta \eta^2 \rangle}, \quad (1)$$

$$C^T = \frac{\langle \delta T \delta \eta \rangle}{[\langle \delta T^2 \rangle \langle \delta \eta^2 \rangle]^{1/2}}, \quad (2)$$

where  $\langle \cdot \rangle$  means time average;  $\delta T$  and  $\delta \eta$  represent the temperature anomaly and the elevation anomaly, which are the instantaneous values minus their time-averaged values. After 6 years' integration, the model results are used, as an approximation of climatologies, to get these coefficients. Mellor and Ezer (1991, 1994) pointed out that these statistical coefficients obtained from the results of the observational climatology are quite similar to those obtained from numerical model.

Second, the “observed” temperature could be simulated with the two parameters obtained above. Then, the surface information from observation can be projected into subsurface layers by

$$\delta T^o(x, y, z, t) = F^T(x, y, z, t) \delta \eta^o(x, y, t), \quad (3)$$

where  $\delta \eta^o$  represents the SLA derived from satellite altimeter;  $\delta T^o$  represents the projected “observed” temperature anomaly.

Eq. (3) can be used to get the “observed” subsurface temperature at the next step of OI assimilation. Eqs (1)-(3) together compose an isotropic correlation model, which plays a key role in the projection based on the correlation between the anomalies at surface and those at the subsurface. Because this “observation” of temperature is not really observed, some error might be produced in the approximation of this isotropic correlation model. This error, as well as the error of the satellite altimeter data, will be taken into account in the procedure of OI assimilation.

Third, the weighting matrix should be estimated by OI analysis. Supposing that the satellite-derived SLA is available at time  $t$ , according the algorithm of OI, the analysis elevation and the analysis temperature at a model grid can be given as

$$\eta_i^a = \eta_i^f + \sum_{\alpha} P_{i\alpha}^{\eta} (\delta \eta_{\alpha}^o - \delta \eta_{\alpha}^f), \quad (4)$$

$$\begin{aligned} T_i^a &= T_i^f + P_i^T [F_i^T (\delta \eta_i^o - \delta \eta_i^f) + \Delta_c T] \\ &= T_i^f + P_i^T [F_i^T \sum_{\alpha} P_{i\alpha}^{\eta} (\delta \eta_{\alpha}^o - \delta \eta_{\alpha}^f) + \Delta_c T], \end{aligned} \quad (5)$$

where the superscript  $a$  and  $o$  represent analyzed and observed value, respectively; the superscript  $f$  represents the value obtained from numerical model (or the so called first guessed value); the subscripts  $i$  and  $\alpha$  represent the grid index and observational point, respectively.  $\Delta_c T$  represents the error derived for the approximation of the isotropic correlation model.  $P_{i\alpha}^{\eta}$  and  $P_i^T$  denote the weighting matrixes for  $\delta \eta^o$  and  $\delta T^o$ , respectively.

Following Ezer and Mellor (1991, 1994), a final express of the weighting matrixes is written as

$$\sum_{\alpha} P_{i\alpha}^{\eta} (R_{\alpha} G_{\alpha\beta} + D_{\alpha} \delta_{\alpha\beta}) = R_i G_{i\beta}, \quad (6)$$

$$P_i^T = \frac{R_i (C_i^T)^2 \sum_{\alpha} P_{i\alpha}^{\eta} G_{i\alpha}}{R_i (C_i^T)^2 \sum_{\alpha} P_{i\alpha}^{\eta} G_{i\alpha} + 1 - (C_i^T)^2}. \quad (7)$$

The definitions of  $R_{\alpha}$ ,  $G_{\alpha\beta}$ ,  $D_{\alpha}$  and  $\delta_{\alpha\beta}$  have been given by Ezer and Mellor (1997).

Lastly, the “observed” temperature should be assimilated into model at each grid by using OI method. When the weights are obtained, a better reconstruction of oceanic states could be generated. Only the temperature is changed directly while the elevation is not influenced by assimilation. An adjustment of density is carried out immediately to satisfy the changes

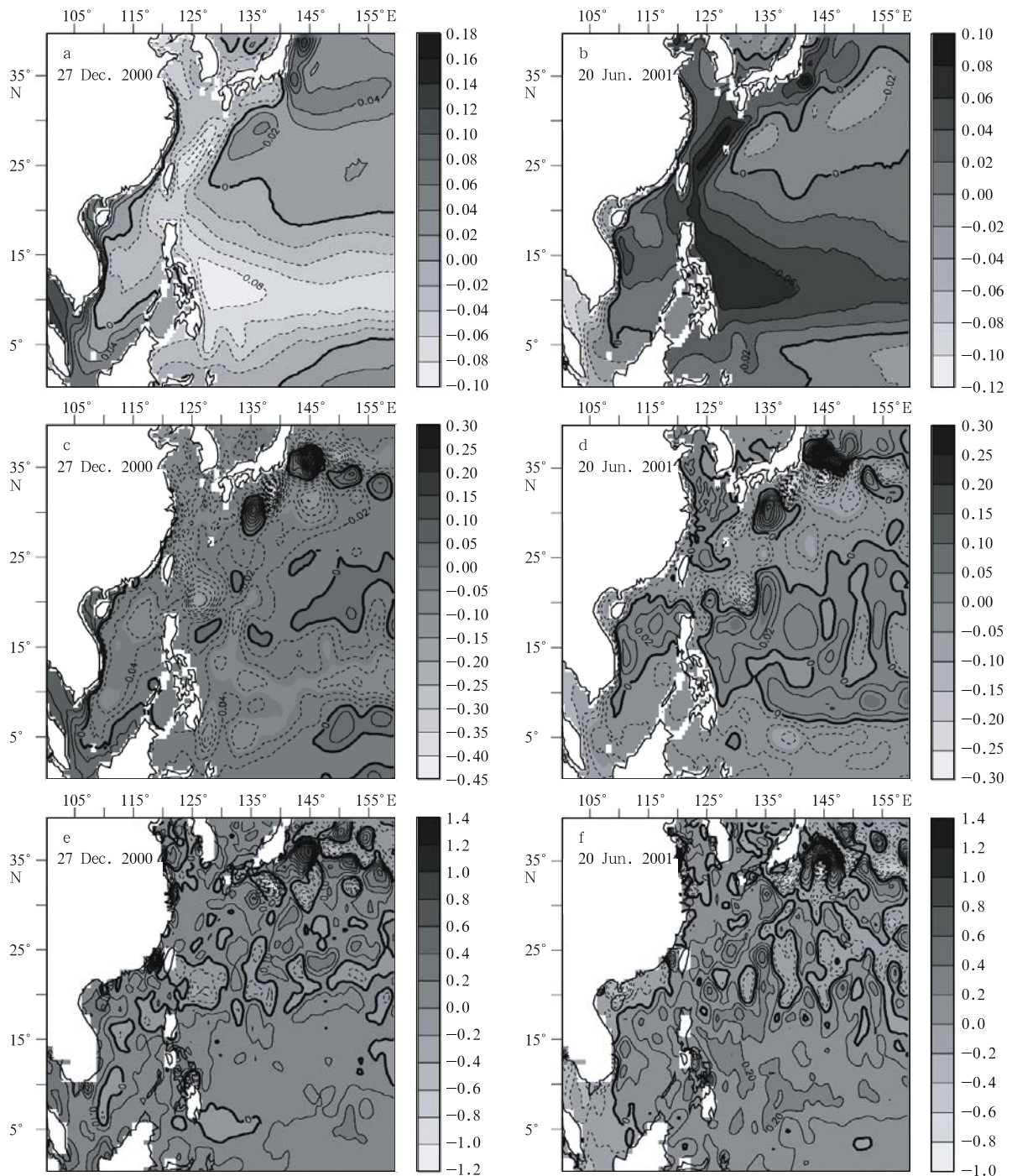
of temperature in the model. Other variables will be adjusted during subsequent integration.

### 3 Validation of the assimilation system

#### 3.1 Sea level anomaly

Temperature is the only variable which is adjusted

directly by satellite SLA during the processes of data assimilation. Thus the modeled SLA can be used to check the performance of the assimilation system. The distributions of SLA in summer and winter are given in Figure 1. In the northwest Pacific Ocean, the distribution pattern of SLA after assimilation shows an apparent similarity to the satellite observation. In most



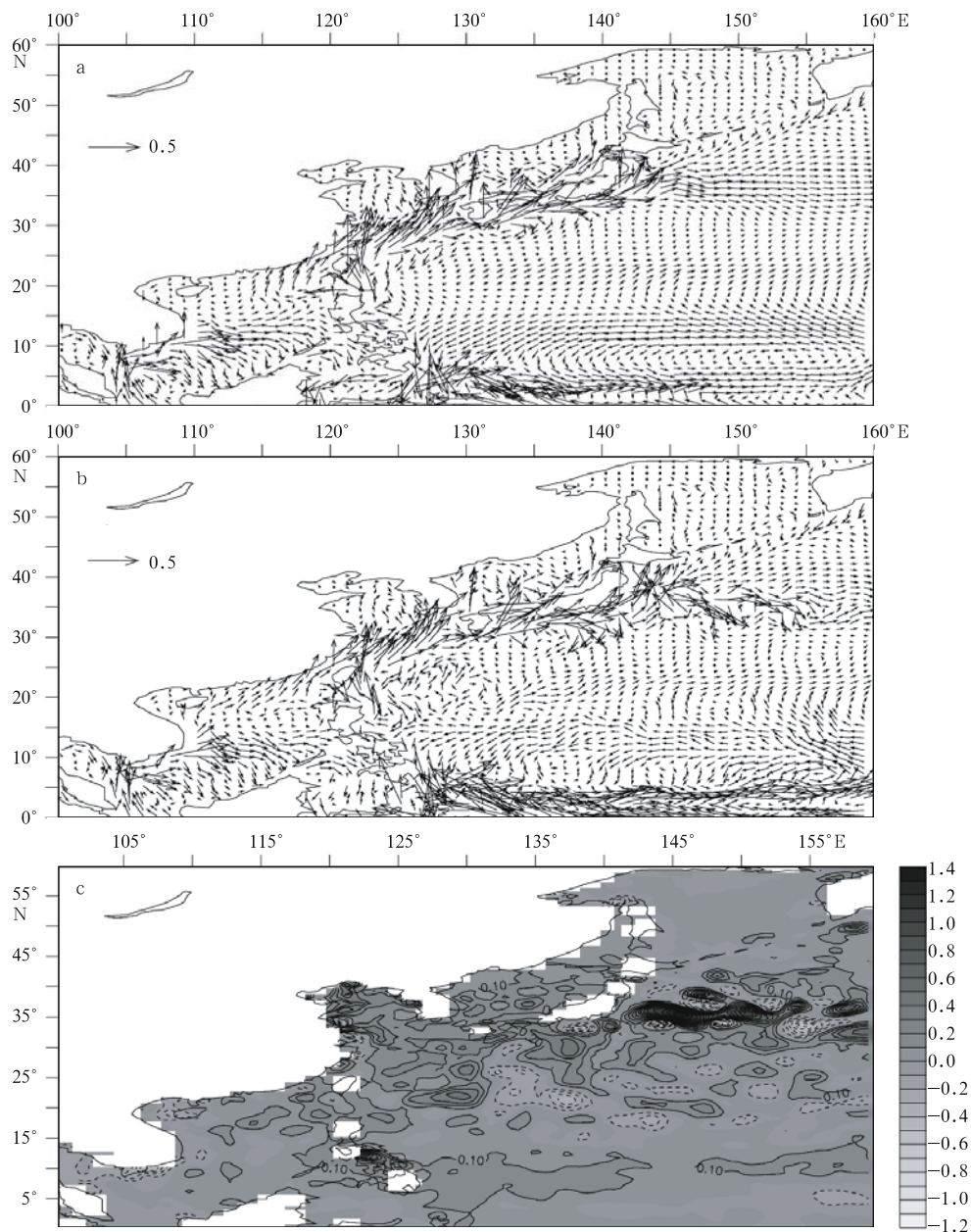
**Fig.1.** Distributions of SLA in the northwest Pacific Ocean. (a) Results without assimilation in summer; (b) Results without assimilation in winter; (c) Assimilation results in summer; (d) Assimilation results in winter; (e) Satellite observation in summer; and (f) Satellite observation in winter.

area, SLA centers appear after assimilation, while the SLA field without assimilation is much smooth. This difference is distinct in the area along the Kuroshio. Besides, the values of SLA without assimilation are much smaller than satellite data. The quantitative increase due to assimilation is about 50% of the result without assimilation. It can be concluded that both the magnitude and distribution pattern of simulated SLA are much improved by data assimilation.

### 3.2 Circulation patterns

The northwest Pacific Ocean and Indian Ocean are chosen as target regions for model validation. The main characteristics of circulation systems remain, and the simulation of fine structures is much improved after assimilation.

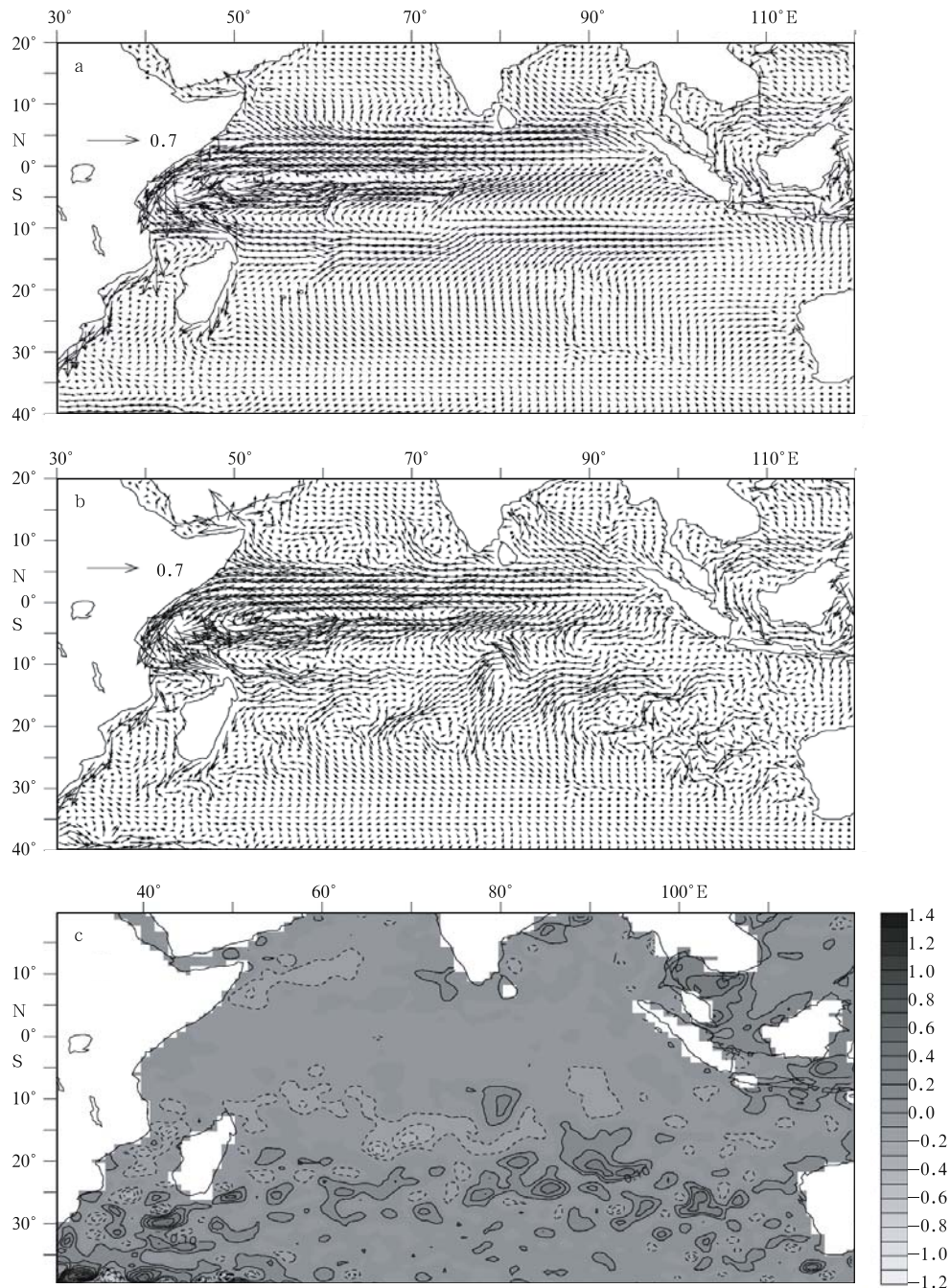
Figure 2 shows that the improvements in eddy reconstruction are evident in the area of Kuroshio



**Fig.2.** Comparisons between (a, b) model results and (c) satellite SLA observation in the northwest Pacific Ocean on 29 August 2001. (a) and (b) denote modeled circulations without and with assimilation, respectively.

and its extension. These eddies approximately match the high/low areas of SLA satellite observation. For instance, in the location of (23°N, 128°E), there is a clockwise eddy in Fig. 2b, which is consistent with the SLA high in Fig. 2c. The model's ability of eddy-resolving is improved by data assimilation, in spite of the fact that some smaller scale systems are not well

resolved because of the low model resolution. The assimilation results in Indian Ocean (Fig. 3) are also better than those from modeling without assimilation. Between 15° to 30°S, the zonal SLA extremes (Fig. 3c) agree well with these eddies in the velocity fields (Fig. 3b).



**Fig.3.** The same as Fig. 2, but in the Indian Ocean on 15 February, 2001.

These analyses indicate that the circulation patterns, especially the eddy structures, are better reproduced after assimilation. These results showed that the method of data assimilation is a good choice to study the oceanic eddies. It should be noticed that the forcing fields of wind and heat flux are climatological. The data assimilation with high time resolution forcing such as daily wind and heat flux data is still needed. And the eddy evolution and three dimensional structures will be further discussed in the next section.

## 4 Reconstruction of eddies

### 4.1 Eddy tracing processes

We traced the developments of several eddies in the study area, and the eddy located in the northwest Pacific is selected to further test the performance of the assimilation system. The tracing period of the eddy was from 29 August to 25 November, 2001. Snapshots of every 10–14 days are shown in Fig. 4. On 29 August, the eddy was located in (22°N, 129°E) occupying about 5 longitudes. The eddy swirled clockwise, moved southwestward, combined with other clockwise eddies, and interacted with its adjacent ones swirling in opposite direction. At the same time the shape of this eddy had been varying; the vorticity strengthened and reached its climax rapidly on 12 Sep. 2001 (the second panel in Fig. 4). During the period of 91 days, the eddy migrated for about 6 degrees, and melted into Kuroshio finally.

Another eddy in the middle of the Indian Ocean in winter was also successfully traced from 27 December 2000 to 11 April 2001 (figure not shown). Since the model forcing are from monthly climatology data set, no such eddies were found at all in the results without assimilation. It again manifests the advantage of data assimilation in the modeling of small scale circulation systems.

### 4.2 Eddy structure analysis

The circulation and the temperature fields for the eddy traced in the northwest Pacific Ocean are given at different depths on 12 September 2001. Results at the depths of 10 m, 20 m, 50 m, 100 m, 200 m, 400 m, 600 m and 800 m are shown (Fig. 5).

The vorticity of this eddy decreased gradually with the increasing of depth. At 10 m, the eddy was located in an area of mixed warm and cold water. On the left side of the eddy, a current flowing toward the Kuroshio formed a warm ridge, while a cold tongue

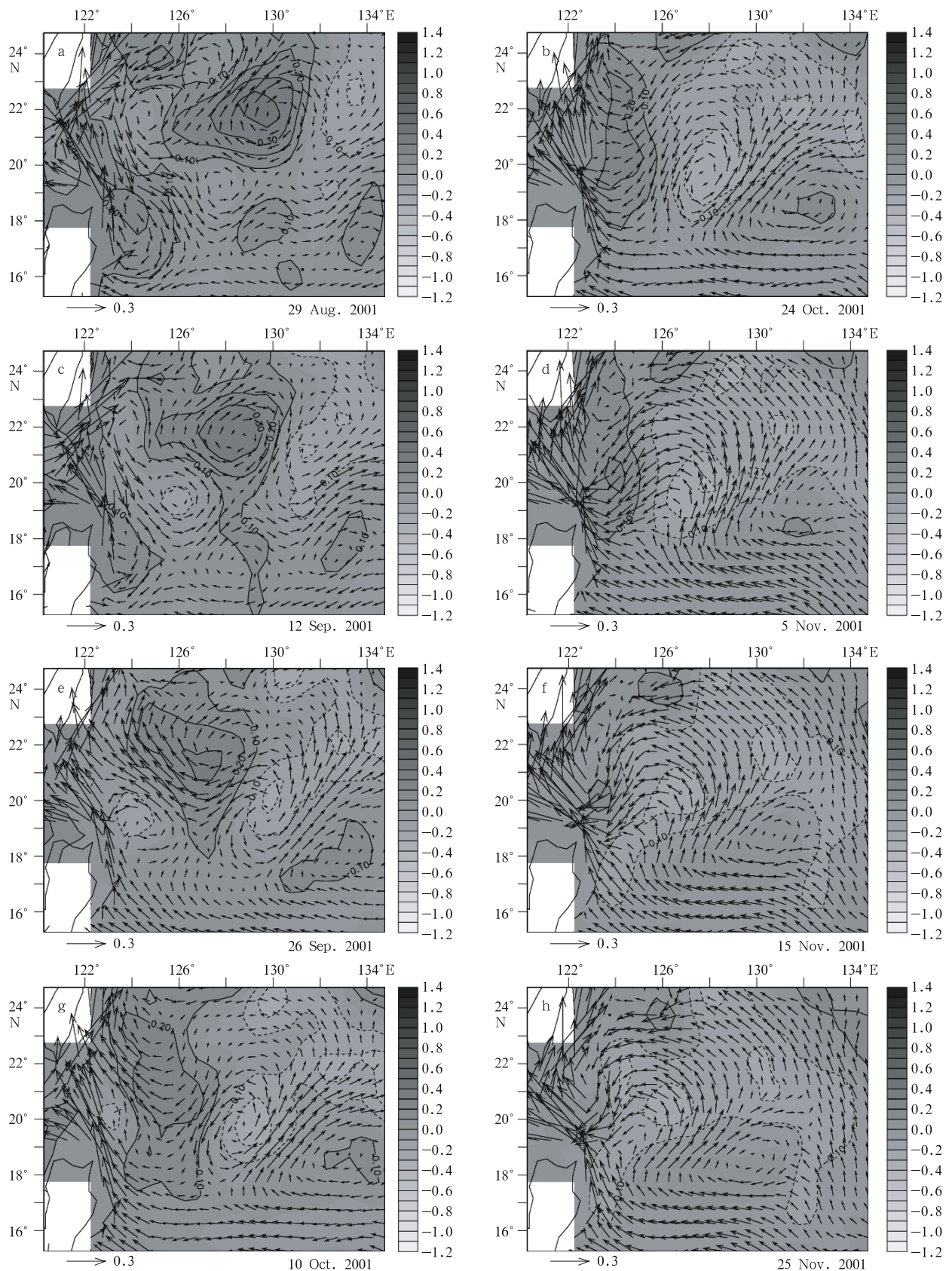
could be found on the right side. These temperature and velocity distributions had typical three dimensional structures: the cold tongue intensified with the increase of depth, and the warm water became weaker and weaker. The eddy was clear at depth from 20 to 200 m. In the layers deeper than 200 m, the temperature showed a simply longitudinal gradient, and this pattern is much different from that on the upper layers. While checking the swirling of this eddy on each layer, it can be found that its horizontal centers slightly lean to southwest in the subsurface. In short, this eddy is warm and cyclonic; its horizontal structure varied among different layers with a decreasing strength with depth.

## 5 Summary and conclusions

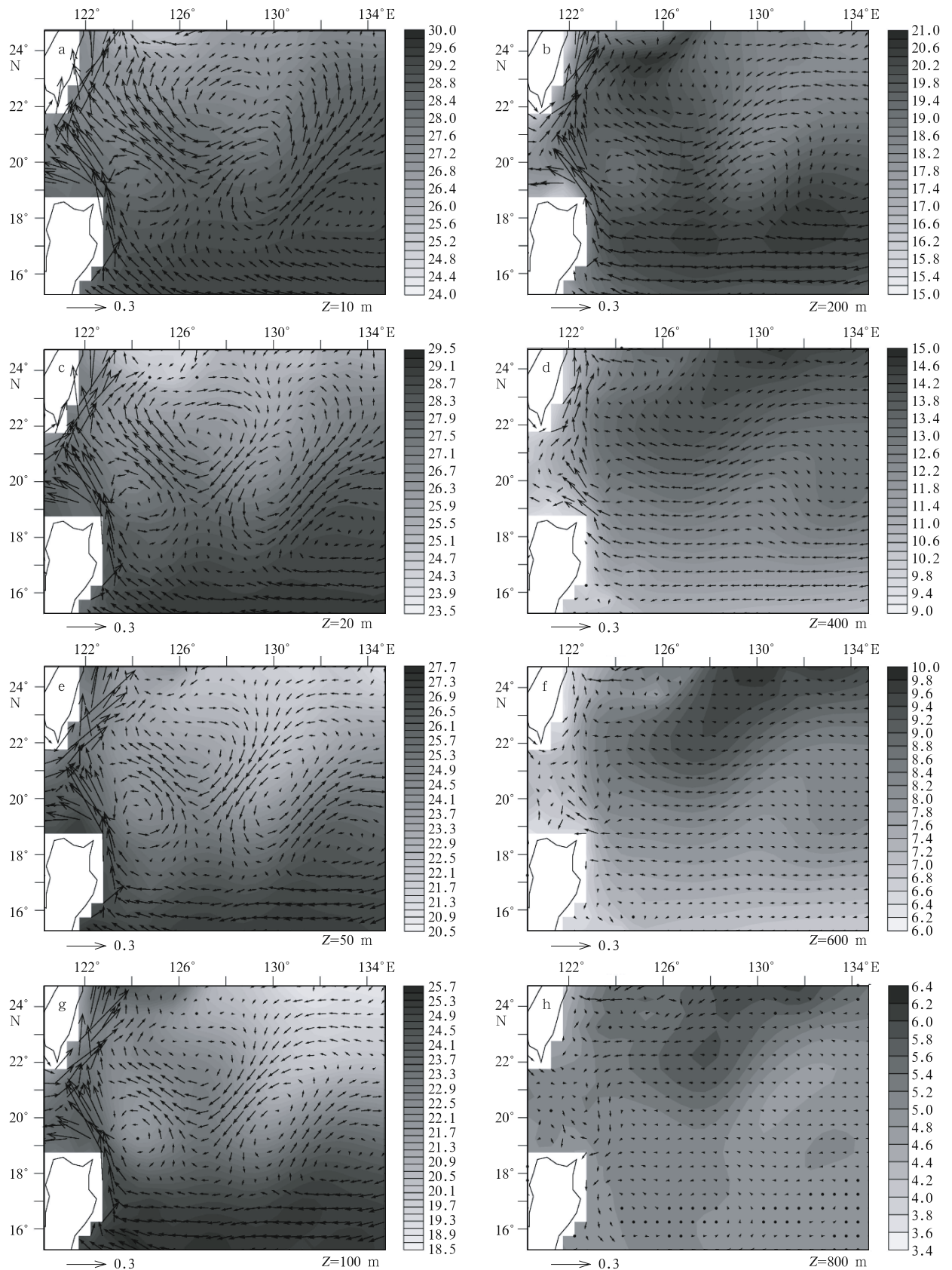
In this study, the satellite SLA data are assimilated into a quasi-global ocean circulation model to get a better simulation of the oceanic environments. On the basis of an isotropic correlation model about the SLA and sea temperature, a modified OI method is used to set up the data assimilation system. This data assimilation system is verified to be reliable and computationally economic. The assimilated model results agree well with observations, which make it justifiable to further analyze the circulation and the fine structures of oceanic eddies.

The evolution of an eddy is traced. This eddy emerged in the northwest Pacific on 26 September 2001, migrated for about 6 degrees southwestward, and joined Kuroshio after three months. During this process, this eddy interacted with the surrounding eddies. Analyses of the three dimensional structure of the eddy denote that the vorticity decreases with the increase of depth, and its horizontal patterns varies on different depths.

There still exist discrepancies between modeling and satellite observation, especially in very fine circulation structures. Increasing the model resolution and improving the model dynamic mechanism, such as wave-circulation coupled process (Qiao et al., 2004b), are prospect to improve the modeling results. On the other hand, further studies should involve more information from observation, e.g., Satellite SST, XBT, Argo profiles, drifter data. Once more observations of high quality are assimilated, the system is believed to be capable of producing better estimates for the oceanic state.



**Fig.4.** The evolution of an eddy in the northwest Pacific Ocean. The dates are shown on each panel.



**Fig.5.** Eddies at different depths in the northwest Pacific Ocean on 12 September 2001. The depths are marked on each panel.

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