ADVANCES IN ATMOSPHERIC SCIENCES, VOL. 30, NO. 4, 2013, 974–982

A New Version of Regional Ocean Reanalysis for Coastal Waters of China and Adjacent Seas

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(Received 10 August 2012; revised 14 November 2012; accepted 16 November 2012)

ABSTRACT

A new regional ocean reanalysis over multiple decades (1958–2008) for the coastal waters of China and adjacent seas has been completed by the National Marine Data and Information Service (NMDIS) under the CORA (China Ocean ReAnalysis) project. Evaluations were performed on three aspects: (1) the improvement of general reanalysis quality; (2) eddy structures; and (3) decadal variability of sea surface height anomalies (SSHAs). Results showed that the quality of the new reanalysis has been enhanced beyond ∼40% (39% for temperature, 44% for salinity) in terms of the reduction of root mean squared errors (RMSEs) for which the reanalysis values were compared to observed values in the observational space. Compared to the trial version released to public in 2009, the new reanalysis is able to reproduce more detailed eddy structures as seen in satellite and in situ observations. EOF analysis of the reanalysis SSHAs showed that the new reanalysis reconstructs the leading modes of SSHAs much better than the old version. These evaluations suggest that the new CORA regional reanalysis represents a much more useful dataset for the community of the coastal waters of China and adjacent seas.

Key words: regional ocean reanalysis, China ocean reanalysis (CORA), improved quality of reanalysis

Citation: Han, G.-J., and Coauthors, 2013: A new version of regional ocean reanalysis for coastal waters of China and adjacent seas. *Adv. Atmos. Sci.*, **30**(4), 974–982, doi: 10.1007/s00376-012-2195-4.

1. Introduction

Since the trial version (also called "the old version") of the regional ocean reanalysis for the coastal waters of China and adjacent seas was made public in 2009 (Han et al., 2011), the CORA (China Ocean ReAnalysis) project in the National Marine Data and Information Service (NMDIS) has been engaged in improving the quality of the reanalysis. Many updates have been made to both the dynamical model and the assimilation algorithm, some of which have had significant impacts in terms of improvements to the quality of the reanalysis dataset. For example, the model topography has been carefully refined according to the ocean topography chart, which greatly improves the model representation in the south and northeast boundary areas, and thereby improves the analysis quality. Second, sea surface height anomalies (SSHAs) retrieved from satellite altimetry data are now converted to pseudo-temperature–salinity (T-S) observations using the Cooper and Haines (1996) scheme with water properties conserved, instead of using the 3D variational (3DVAR) method for single profiles, as in the old version. Third, the T-S relationship used in the multi-grid 3DVAR (Li et al., 2008, 2010; Han et al., 2011) in the new version is established by using an interpolation algorithm based on the instant model T-S data table, instead of a polynomial fitting algorithm as in the trial version. While improving the analysis quality, these new algorithms have also significantly sped up the reanalysis procedure, making it possible to produce longer time series of reanalysis oceanic states. The new reanalysis starts from 1958 and has been completed over 50 years (up

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to 2008). Evaluations have shown that it fits observations much better and has a better representation of oceanic states. As the trial version of CORA has exhibited its favorable performance already in the representation of regional oceanic circulation (Han et al., 2011; Wang et al., 2011, 2012; Xing et al., 2012; Yu et al., 2012; Wu, et al., 2013), we expect the new reanalysis (referred to as version 1.0 hereafter) provides a more useful dataset for regional oceanic circulation studies, including decadal variability.

This paper reports a thorough evaluation of the CORA version 1.0 reanalysis by comparing it with the trial version and observations. After briefly describing the methodology, including updates to the model configuration and the assimilation method in section 2, we present the evaluation in section 3 in three aspects: (1) improvement of the quality of reanalysis temperature and salinity; (2) the representation of eddy structures; and (3) the structure and variability of SSHAs. Finally, a summary and discussion are given in section 4.

2. Methodology

2.1 *The model and assimilation method*

A trial version of the regional ocean reanalysis dataset, which is focused on the coastal waters of China and adjacent seas, was released in 2009 (http://www.cora.net.cn) under the CORA project initialized by the NMDIS. However, the dataset only spans a period of 23 years, starting from January 1986. The model domain in the new version is the same as the old version (10°S–52°N in latitude and 99°–150°E in longitude, including the Bohai Sea, the Yellow Sea, the East China Sea, the South China Sea, and adjacent seas), but the new reanalysis spans a much longer period, starting from January 1958 to 2008. Here, we first provide a brief description of the model configuration, and then comment on the major updates of the assimilation algorithms.

The ocean dynamical model used is the same as in the old version, i.e., a parallel version of the Princeton Ocean Model with a generalized coordinate system (POMgcs) (Mellor et al., 2002; Ezer and Mellor, 2004) developed by the NMDIS. In order to deepen the mixing layer in the simulation, we introduced a wave-breaking parameterization (Mellor and Blumberg, 2004) into the vertical mixing scheme of POMgcs. By prescribing a tidal open boundary condition, we also introduced the tidal mixing effect into the model, to give a better representation of the tidal front in the coastal region. Eight major constituents were considered: four semidiurnal tides (M_2, S_2, N_2, K_2) and four diurnal tides (K_1, O_1, P_1, Q_1). The model spatial resolution was $(1/8)^\circ$ in the region of Kuroshio (19°–33°N, 117°–130°E), covering a part of the East and South China Seas. A coarser grid of $(1/2)^\circ$ was employed toward the Pacific Ocean. The mixed vertical grid of sigma and z-level was used, with a total of 35 levels and a maximum depth of 5035 m for configuration.

The details of the implementation of the data assimilation scheme for the CORA trial version can be found in Han et al. (2011). Here, we only provide comments on the major points at first, and then describe the updates for the new reanalysis:

(1) The framework of the ocean data assimilation scheme was based on the multi-grid 3DVAR (Li et al., 2008, 2010). The cost function is first minimized on coarse grids to obtain longwave information, and the grid resolution increases so that the minimized cost function retrieves shortwave information. The final adjustment of an analysis field is the sum of adjustments as the spatial scale is refined from coarse to fine.

(2) The salinity adjustment scheme proposed by Troccoli et al. (2002) was employed.

(3) A 3DVAR scheme (Yan et al., 2004; Zhu and Yan, 2006; Zhu et al., 2006; Xiao et al., 2006, 2008; Shu et al., 2009, 2011; Wang et al., 2012a, b) was adapted (He et al., 2010) to convert altimetry SSHAs into temperature and salinity "pseudo observations" for each single water column.

(4) The assimilation was performed every day, and a seven-day time window was used to incorporate SSHA information from altimeters, SST data from remote sensing satellites, and in situ temperature and salinity profiles (above 1000 m) into the model.

Based on the fundamental assimilation system, the construction described above in the CORA trial version (Han et al., 2011), a few updates have been implemented in the CORA new version (version 1.0). The major updates include four aspects. First, the model topography has been refined carefully according to the ocean topography chart, as shown in Fig. 1. The model spin-up was performed for 20-yr integration started from observed temperature and salinity climatology driven by multi-year monthly mean air forcing, followed by 20-yr integration driven by monthly mean air forcing in the year 1952, while 40-yr integration was implemented for the model spin-up in the trial version, started from observed monthly mean temperature and salinity climatology driven by multi-year monthly mean air forcing. 6-yr data assimilation spin-up was performed for reanalysis initialization as in the trial version. 72-hour triple smooth filter was applied to the daily model output for tide removal, compared to 25-hour average used in the trial version. Second, the data assimilation is performed at a depth of the

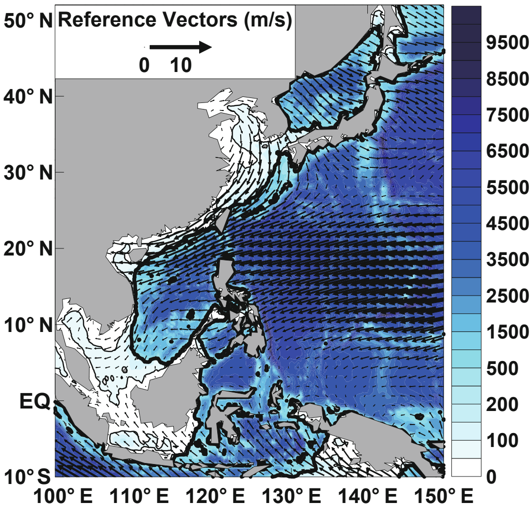

Fig. 1. Reanalysis domain, topography (units: m) and climatological wind field (units: m s^{-1}). Thick black line: 200-m isobath; thin black line: 50-m isobath.

upper 2000 m, instead of 1000 m as in the old version. Third, SSHAs retrieved from satellite altimetry data are converted to pseudo T-S observations using the Cooper and Haines (1996) scheme with water properties conserved, instead of the 3DVAR method of Yan et al. (2004) employed in the old version. Fourth, the T-S relationship used in the multi-grid 3DVAR in the new version is established by an interpolation algorithm based on the instant model T-S data table, instead of a polynomial fitting algorithm as in the old version (Han et al., 2011). The updated algorithms in the new version are much faster (doubling the assimilation speed) than the old version, thus enabling a longer oceanic state reconstruction to be produced (currently completed from 1958 to 2008).

2.2 *Observational data and atmospheric forcing*

The observational data used in the new version are a collection of all available observations including in

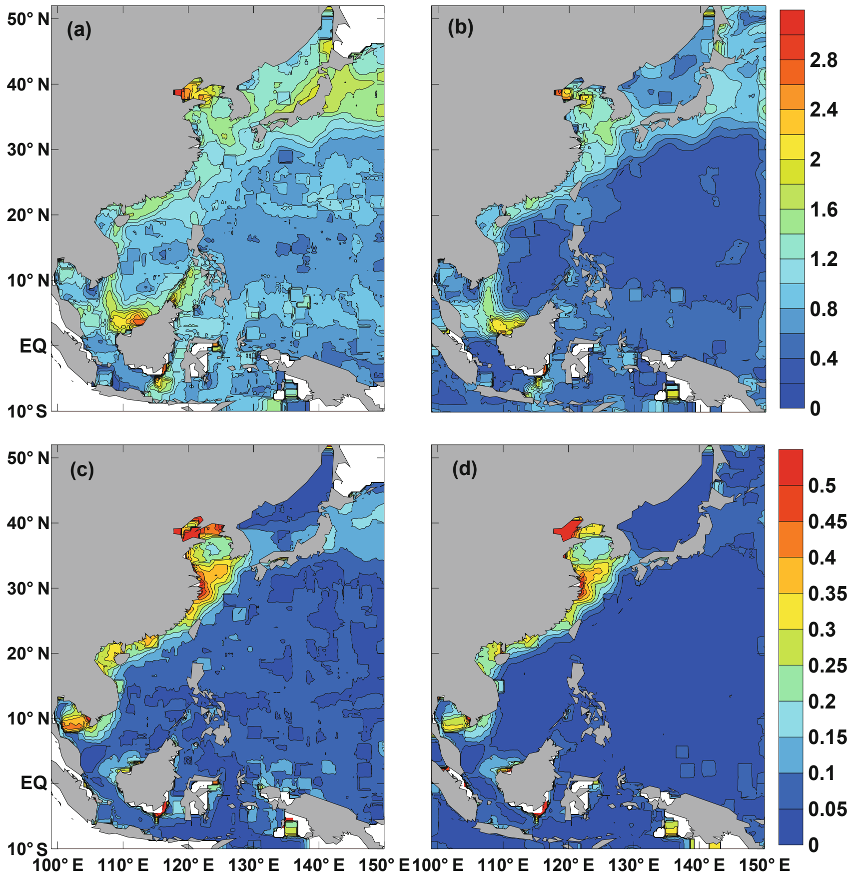

Fig. 2. Horizontal distribution of RMSEs of temperature (units: °C, upper panels) and salinity (bottom panels) above 1000 m for the CORA trial version (left panels) and version 1.0 (right panels).

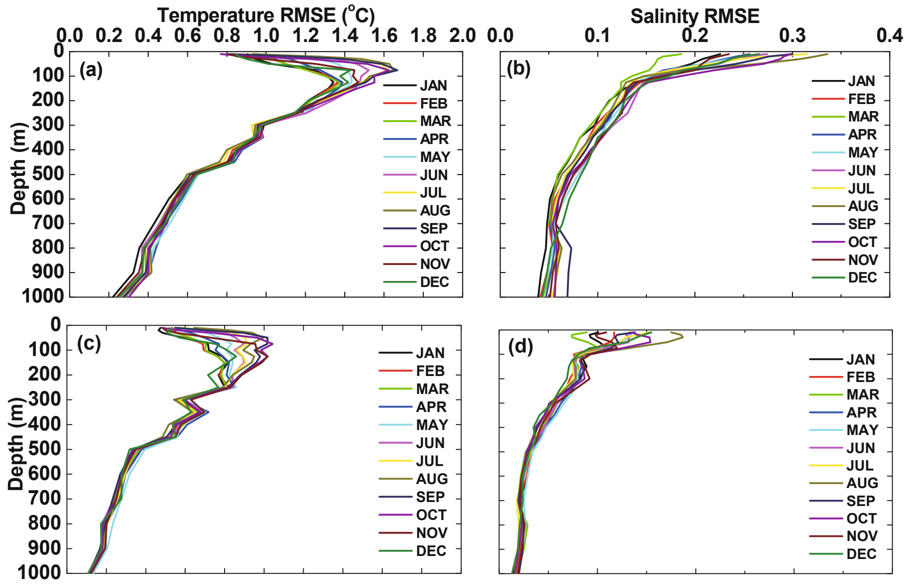

Fig. 3. Vertical distribution of monthly mean RMSEs of temperature (units: °C, left panels) and salinity (right panels) reanalysis for the CORA trial version (top panels) and version 1.0 (bottom panels).

situ temperature/salinity profiles, SSHAs from altimeters, and SSTs from remote sensing satellites. A great deal of effort was devoted to conduct a pre-assimilation quality control to ensure the quality of the analysis. For example, the temperature and salinity profiles from CTD, Nansen bottle, XBT, Argo, etc. used in the study were subject to unified quality control, including position/time check, depth duplication check, depth inversion check, temperature and salinity range check, excessive gradient check, and stratification stability check etc. In particular, the drifting errors associated with Argo (array for real-time geostrophic oceanography) salinity profiles were calibrated by employing the calibration method developed by Wong et al. (2003).

The climatology of the wind field used in the reanalysis system is shown in Fig. 1. From 1 July 1987 to 31 December 2008, the wind field employed was the cross-calibrated multi-platform (CCMP) (Atlas et al., 2011) daily mean wind with a horizontal resolution of $0.25° \times 0.25°$ (comparatively, QuikSCAT wind was used in the old version from 1 July 1999 to 31 December 2008). For the rest of the analysis period, the wind field was obtained from the US National Centers of Environmental Prediction (NCEP) reanalysis, with a spatial resolution of $1.875° \times 1.875°$, and a temporal resolution of 6 hours. The bulk formula was used to calculate wind stress. The heat and water flux were also taken from the NCEP reanalysis. No river runoff was considered in this study. Sea level, temperature, salinity, and currents specified on the open boundary came from the SODA (simple ocean data assimilation) reanalysis (Carton and Giese, 2008), and all of these were the same as used in the old version.

3. Evaluation of reanalysis results

3.1 *General improvement in the quality of the reanalysis*

We first produced the error statistics to compare the quality of CORA version 1.0 and the trial version. Figure 2 shows the vertical averaged RMSEs of temperature (upper panels) and salinity (bottom panels) above 1000 m in the old (left panels) and new (right panels) versions over 23 years (1986–2008), which is the length of the reanalysis dataset in the old version. It is worth noting that the reanalysis states were projected on the observational space for verification. From Fig. 2, it can be seen that the level of error in the new reanalysis version is much smaller than in the old version for both temperature and salinity. For the whole domain, temperature RMSE was on average reduced by 39% (from 1.14°C to 0.7°C) and salinity RMSE by 44% (from 0.18 to 0.1). The domain-averaged RMSEs with respect to depth over 12 months were calculated for both versions using data taken from 1986–2008. As shown in Fig. 3, the error reduction in the new version was very significant throughout all depths over total 12 months. For example, while the 12-month mean RMSE of sea surface temperature (salinity) was reduced to 0.6°C (0.15) from 0.9°C (0.25), the corresponding RMSE at 1000 m was reduced to 0.1°C

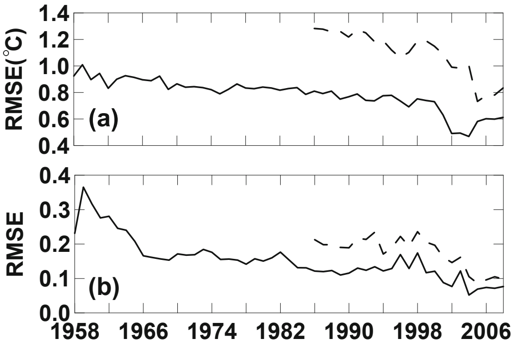

Fig. 4. Time series of RMSEs of (a) temperature (units: °C) and (b) salinity for the CORA trial version (dashed line) and version 1.0 (solid line).

(0.025) from 0.3°C (0.05). We also calculated the monthly mean RMSEs in the 3D model domain to form the time series shown in Fig. 4. It can be seen clearly that the new reanalysis (solid line) was superior to the old version (dashed line) over the time period available for comparison.

3.2 *Eddy structures*

This section evaluates eddy simulation in the new reanalysis version. We selected four typical active eddy areas to compare the eddy structures in the new and old reanalysis products. Figures 5–8 present the different eddy structures in the South China Sea on 14 August 2000 (Fig. 5), in the seas to the south of Japan on 5 February 2002 (Fig. 6), in the east of Ryukyu on 20 October 2002 (Fig. 7), and at Kuroshio Meander on 25 July 1987 (Fig. 8). Except in Fig. 8, for which the altimetry SSHA data are not yet available, meaning no observed SSHA field is shown, the middle-upper panels in all figures otherwise always show the satellite-observed SSHAs. While the left (right) column panels show the new (old) version results, the middle-bottom panels always present the observed temperature distribution in the vertical section along with positions denoted by a series of solid-black dots in the upper panels. A common phenomenon in Figs. 5–8 is that, compared to the old version, the new version was able to reproduce more detailed eddy structures as seen in satellite and in situ observations. For example, while the old reanalysis only produced flat isotherms in the east of 112°E in the vertical section for the case of the South China Sea on 14 August 2000 (Fig. 5), the new reanalysis showed a warm ridge that was more consistent with observations. As for ocean eddies occurring at Kuroshio Meander on 25 July 1987 (Fig. 8), while the warm ridge apparently shifted to the south of 30°N in the old reanalysis, the warm-ridge position was corrected to the north in the new version, providing results that were very close to observations. Another example is the correction of the cold-core position in the east-of-Ryukyu case on 20 October 2002 (Fig. 7) in which the cold-core was apparently shifted to the east of 128°E in the old reanalysis, instead of saturating at the longitude as shown in observations and the new reanalysis. In addition, we can see significant improvement in the eddy structures in the deep part (below 250 m) in the four cases.

3.3 *SSHA distribution and variability*

Figure 9 shows the EOF spatial modes for SSHAs obtained from CORA version 1.0, the trial version, and altimetry observations. It is clear that the pattern in the new version is very close to that of the altimetry observations in most areas including the subtropical countercurrent area and South China Sea, while the old version is not. Figure 10 shows the time series of the first principal component (PC1) for CORA version 1.0, the trial version, and altimetry observations. We can see that the new reanalysis, where correlation with altimetry observations was as high as 0.93, is superior to the old version, where correlation with altimetry observations was 0.73, over the time period available for comparison.

4. Summary and discussion

With updates to the model configuration and the assimilation algorithm, a new regional ocean reanalysis for the coastal waters of China and adjacent seas has been completed for a greater than 50-yr period by the NMDIS under the CORA project. Evaluations showed that, compared to the old CORA reanalysis dataset, the quality of the new reanalysis (CORA version 1.0) has been enhanced beyond ~40% (39% for temperature, 44% for salinity), as measured by RMSEs. The new version is able to reproduce more detailed eddy structures, as observed by altimetry and in situ stations. The new reanalysis also reconstructs the signals of the leading modes of SSHAs much better than the old version. These evaluations showed that the new CORA regional reanalysis establishes a more useful dataset for the community of the coastal waters of China and adjacent seas for both research and operational purposes.

Although the analysis errors along the coastal regions of China in this new version have been reduced compared with the old version, large analysis errors, particularly for salinity, still exist compared with open waters. The inclusion of river runoff in the model and the collection of more historical ocean observations to cover relatively data-sparse regions are another two considerations that could help relieve such large analysis errors, besides increasing the model's resolution.

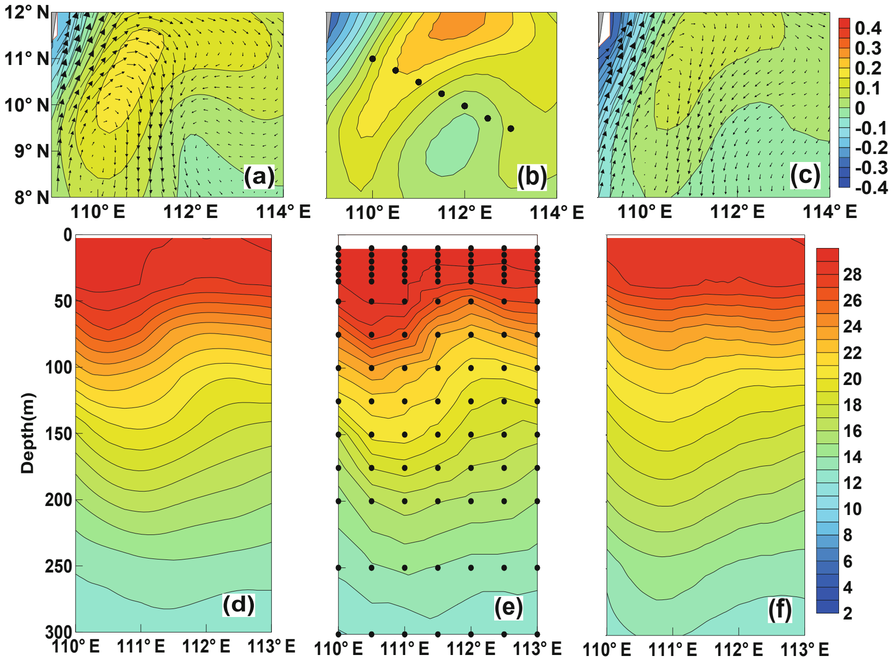

Fig. 5. Ocean eddies located in the South China Sea on 14 Aug 2000: (a, c) SSHAs (units: m) and currents from the CORA version 1.0 and trial version, respectively; (b) altimetry SSHAs (units: m), with the black dots representing observational stations of in situ temperature profiles; (d–f) temperature (units: °C) sections from the CORA version 1.0, observations and the CORA trial version, respectively. Note that the black dots in (e) represent the observational stations.

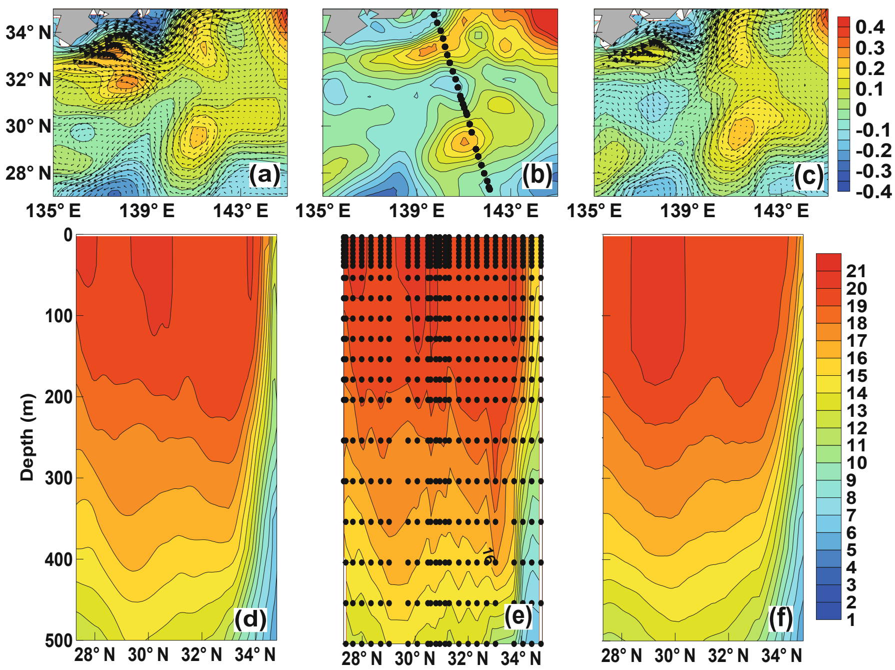

Fig. 6. The same as Fig. 5, but for ocean eddies located in seas to the south of Japan on 5 Feb 2002.

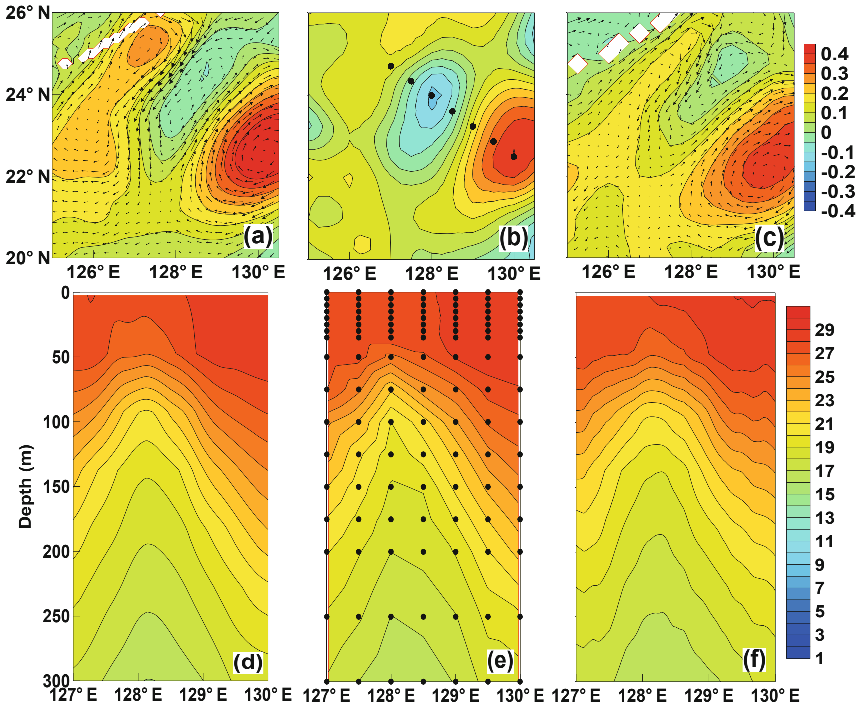

Fig. 7. The same as Fig. 5, but for ocean eddies located to the east of Ryukyu on 20 Oct 2002.

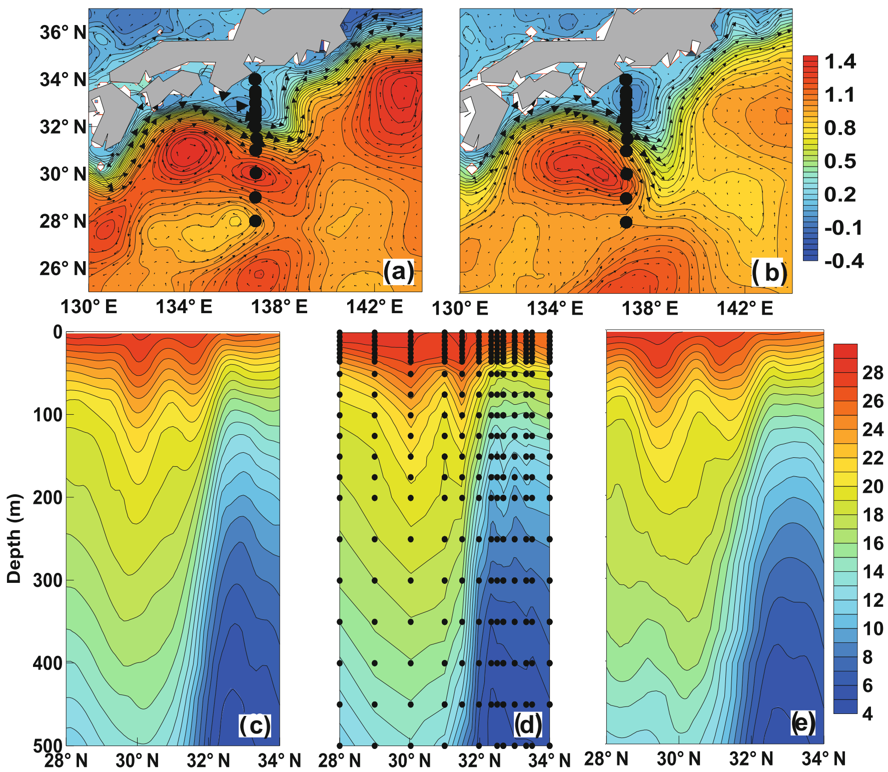

Fig. 8. The same as Fig. 5, but for ocean eddies located at Kuroshio Meander on 25 Jul 1987. Note that no altimetry SSHA observations were available.

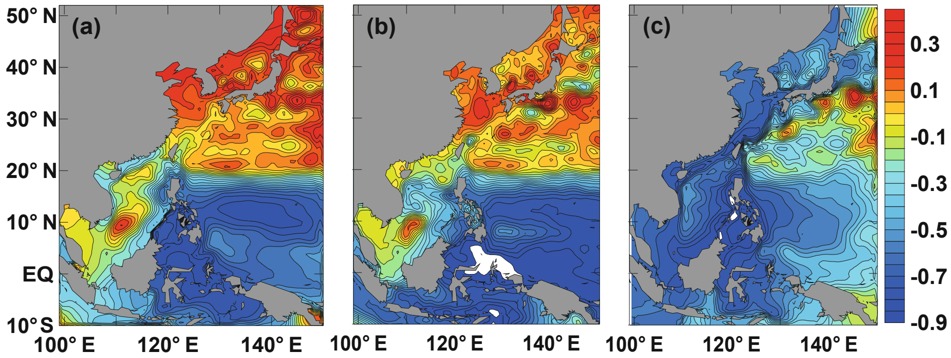

Fig. 9. The first EOF normalized spatial mode of (a) CORA version 1.0, (b) satellite altimetry observations, and (c) the CORA trial version.

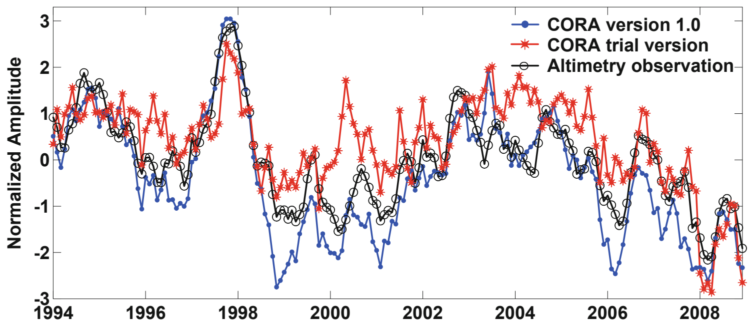

Fig. 10. The temporal series of the first principal component (PC1) for CORA version 1.0 (blue line with dots), the CORA trial version (red line with stars), and satellite altimetry observations (black line with circles).

In addition, an isentropic adjustment scheme within a 3D variational framework is currently being tested, and is expected to further improve the consistency of observational constraints due to better description of ocean flows.

Acknowledgements. This research was sponsored by the National Basic Research Program (Grant No. 2013CB430304) and National Natural Science Foundation of China (Grant Nos. 41030854, 41106005, 41176003, and 41206178), and National High-Tech R&D Program (Grant No. 2013AA09A505) of China. The altimetry SSHA data were obtained from http://www.jason.oceanobs. com, the NCEP reanalysis data from ftp://ftp.cdc.noaa.gov/pub/datasets/necp.reanalysis2, the CCMP ocean surface wind data from PO.DAAC (http://podaac.jpl.nasa.gov/DATA_CATALOG/ccmpinfo.html), and the SODA reanalysis data from http://dsrs.atmos.umd.edu.

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