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Development of the Korea Ocean Prediction System

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Abstract : We describe here the Korea ocean prediction system that closely resembles operational numerical weather prediction systems. This prediction system will be served for real-time forecasts. The core of the system is a three-dimensional primitive equation numerical circulation model, based on σ-coordinate. Remotely sensed multi-channel sea surface temperature (MCSST) is imposed at the surface. Residual subsurface temperature is assimilated through the relationship between vertical temperature structure function and residual of sea surface height (RSSH) using an optimal interpolation scheme. A unified grid system, named as [K-E-Y], that covers the entire seas around Korea is used. We present and compare hindcasting results during 1990-1999 from a model forced by MCSST without incorporating RSSH data assimilation and the one with both MCSST and RSSH assimilated. The data assimilation is applied only in the East Sea, hence the comparison focuses principally on the mesoscale features prevalent in the East Sea. It is shown that the model with the data assimilation exhibits considerable skill in simulating both the permanent and transient mesoscale features in the East Sea.

Key words : operational prediction, data assimilation, mesoscale feature, Korean waters.

1. Introduction

Target area of the Korea ocean prediction system includes the Yellow Sea, the East China Sea, the southern sea of Korea, and the East Sea. These are mid-latitude semi-enclosed basins of considerable regional importance due to increasing pollution. The Yellow Sea and the East China Sea are shallow and tidally-dominated. The East Sea consists of three major abyssal basins deeper than 2000 m and is frequently called a miniature ocean. Realization of their importance has led to many observational and modeling studies during the last decade or so. Modeling the tides in the Yellow Sea and East China Sea, and the circulation in the East Sea have been attempted using various models. However, numerical modeling studies comprising the entire Korean waters are relatively few. While it is challenging to model the entire Korean waters that are subject to different physical forcing, concerns for environmental protection has long required the establishment of an operational ocean prediction.

Given the complexity of the area, it may seem to be premature to attempt to forecast the currents and thermohaline structure of the seas on a daily basis. However, we will show that the modeling system can generally make useful nowcasts and is also a useful research tool. The continuous nowcasts / forecast products employing an assimilation technique of observational data provide a unique approach in forecasting the oceanographic structure with high temporal variability. The continuous products of the oceanographic structure will also provide a basis for understanding physical processes of various scales occurring in the seas.

A unified grid system, named as [K-E-Y], that covers the entire seas around Korea was proposed (Suk *et al.* 1996). They ran the East Sea circulation model (EC model), whose domain was extracted from the [K-E-Y] grid system, up to 7 years (or 2560 days from the initial

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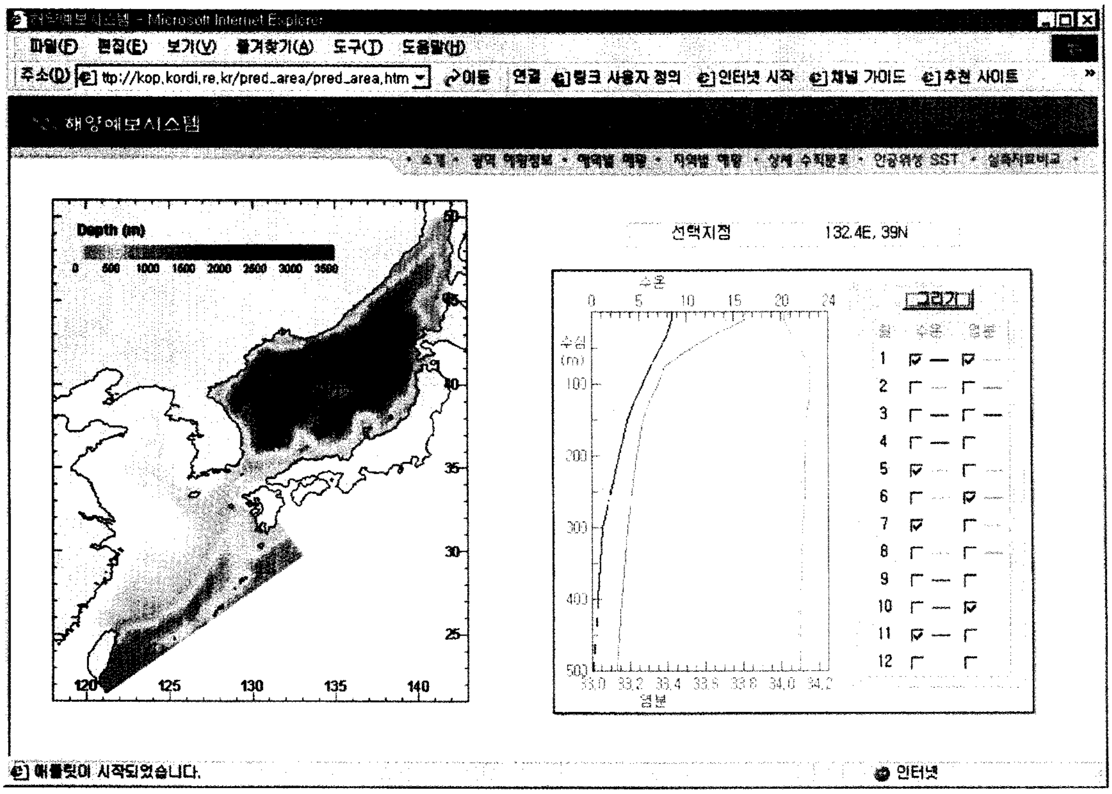

Fig. 1. KC Model domain is shown on the operational data service web site.

condition). The model stability seemed to be obtained in the 4th year.

In this paper, we present results of the KC model that is the Korea ocean prediction system covering the entire Korean waters (Fig. 1). The model is designed for real-time operational forecasts. The methodology is similar to that practiced in meteorology, and to our knowledge this is the only effort that deals with the entire Korean waters. In particular, the focus of this study is constructing one model for the entire Korean waters and building upon data assimilation scheme for the operational purposes. We specifically investigate the role of the data assimilation in producing the permanent and transient mesoscale features in the East Sea. Modeling system and the data-assimilation scheme used in the study are briefly described in sections 2 and 3. Model results from the data assimilation model and non-assimilative model are presented and compared in section 4 with discussions.

2. Modeling system

The core of the modeling system is a primitive equation, three-dimensional circulation model commonly called the Princeton Ocean Model (Blumberg and Mellor 1987; Mellor 1991). Monthly mean sea-surface winds (Hellerman and Rosenstein 1983), sea surface temperature and salinity from analyses and atlases for the region are used as the surface forcing. The initial fields of temperature and salinity are from the January historical data (JODC 1975; Levitus 1982).

The circulation model covers the entire Korean waters so that open boundaries in the model include the Taiwan Strait, Tokara Strait and Kuroshio region in the East China Sea, and the Tsugaru and Soya Straits in the East Sea. A unified grid system, named as [K-E-Y], that covers the entire seas around Korea (Suk *et al.* 1996) is reused. The grid resolution is comparable to or better than the internal radius of deformation in the East Sea. There are 18 σ-levels in the vertical. The imbedded turbulence closure submodel is an improved mixing formulation of Kantha and Clayson (1994).

The model bathymetry was initially smoothed. However, it is well known that models using σ-coordinates are subject to pressure gradient errors over steep bathymetry (Haney 1991; Mellor *et al.* 1994). The magnitude of these errors is largely dependent on the horizontal and vertical resolutions of the model. The realistic bathymetric slopes along the shelf break and escarpments are often too steep for our model configuration to be resolved. For this reason, additional nonlinear filtering of the bathymetry was performed to limit the maximum steepness of the model bathymetry.

Boundary condition and volume transport at the open boundary are summarized in Table 1. Volume transports across all open boundaries are fixed in time. Inflows to the model domain involve the transports across the Taiwan Strait and the Kuroshio in the East China Sea. The latter is set to be 28.0 Sv (1 Sv = 10^6 m^3/s), which is about 23 % larger than a recent estimate of 21.5 $\pm$2.5 Sv based on the 20-month long direct observation east of Taiwan (Johns *et al.* 2001). Outflows consist of the transports across the Tsugaru and Soya Straits in the East Sea, and across the Tokara Strait. A constant volume transport of 27.2 Sv is prescribed in the Tokara Strait, and the difference between the total inflows and outflows is set to flow out of the East Sea through the two straits in the East Sea. The inflow/outflows set in Table 1 constraint the volume transport across the Korea Strait to be 2.3 Sv. This amount is comparable to the estimates based on measurements with the two arrays of bottom-mounted acoustic Doppler current profilers extended over the entire Korea Strait (Perkins *et al.* 1999; Teague *et al.* 2001). Observed temporal variations of the volume transports of the Kuroshio in the East China Sea (Johns *et al.* 2001) and the Tsushima Current across the Korea Strait (Teague *et al.* 2001) are not considered in the present modeling, and the variations will be incorporated in the future modeling efforts. 90 % of the influx flows out across the Tsugaru Strait and the remains across the Soya Strait.

Table 1. Boundary condition and volume transport at model open boundaries.

Open Boundary	Transport (Sv)
East of Taiwan (Inflow of Kuroshio)	28.00
Taiwan Strait	1.50
Tokara Strait	27.2
Tsugaru Strait	2.07
Soya Strait	0.23
Boundary Condition	
Elevation	No gradient
External velocity	Prescribed
Internal velocity	Olranski radiation condition
Temperature and Salinity	Upstream condition

We ran the KC model for 7 years with the climatological forcing. The stability of the KC model seems to be obtained after 4 years of model run. The sea surface elevation, which represents the barotropic circulation, is an important benchmark for the oceanographic condition. Therefore we examined the general pattern of the sea surface elevation in the entire Korean waters and found that they are generally consistent with well-known features in the Korean waters. In order to relax the climatological ocean circulation to that on a real time basis, we switch the surface boundary condition from the climatological temperature to MCSST products while keep using climatological salinity as the boundary condition for surface freshwater flux. The spatial resolution of MCSSTs is about 8 km, and they are generally accurate to about 0.7-0.8°C (Emery *et al.* 1993).

Temporal and spatial interpolations are applied when the MCSSTs show temporal gaps and where they are not available. The meteorological forecasts and the satellite data are available in near real time, and the circulation modeling system is designed to incorporate them to make continuous up-to-date forecasts. In terms of concept and general construction, although not in all of the details, our modeling system bears much resemblance to operational numerical weather forecast models.

3. Data assimilation

The data assimilation is performed by nudging as used in an optimal interpolation (OI)-based analysis (Daley 1991). For data assimilation the most useful and available data are the residual sea surface heights (RSSH) that contain information on vertically integrated dynamic structure of a water column. We assume that the relationship between vertical temperature structure function (EOF) and dynamic height calculated from historical subsurface temperature profile database shown in Fig. 2 (KORDI 1991) is similar to that between EOF and RSSH. Therefore residual subsurface temperature can be obtained via relationship between EOF and RSSH.

The assimilation is performed on constant depth surfaces by redefining the temperature there. In order to do this, the appropriate model variable is interpolated from the σ-levels to the depth levels. The assimilation is performed, and then the new values are interpolated back to the original σ-coordinates. The assimilation procedure, the process of replacing the original model values with modified ones, requires the interpolation of data values at each timestep to every model grid points. To achieve this, we use the univariate statistical interpolation procedure, commonly called OI, as described by Daley (1991) or Bretherton *et al.* (1976). The assimilation is performed on 16 different levels, densely spaced near the surface, down to a maximum depth of 500 m. The nudging period was taken to be 10 days for RSSH. This is because that a sudden insertion of new temperature values occasionally causes numerically unstable behavior. An advantage of OI is that the procedure produces a formal measure of the uncertainty of the OI analysis. The nudging coefficient is modulated by the uncertainty so that the nudging coefficient is zero if the uncertainty shows that the OI analysis has no skill.

Horton *et al.* (1997) used the Gaussian autocorrelations in time and space. The temporal and spatial decay scales are taken to be 14-day and 100 km (constant), respectively. We could use a scale that varies with depth. However, that would have meant re-computing the coefficients at each depth, which would be computationally costly. Therefore we just compute the coefficients once at each grid point for profile data and apply them to all depths. The OI procedure allows for the specification of the uncertainty of the data to be assimilated, and this uncertainty can have spatially correlated and uncorrelated components. For simplicity and because of our insufficient information on error, we assumed that the observation error variance is uncorrelated and 10 % of the background variance.

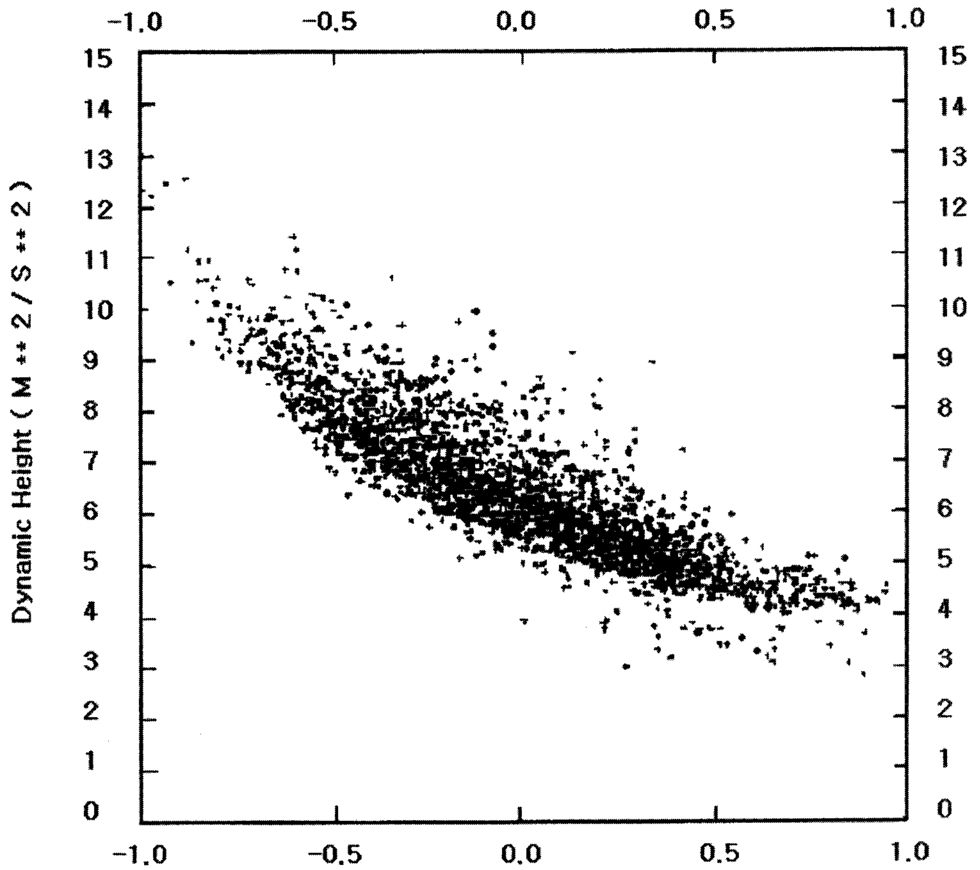

Fig. 2. Comparison of the dynamic height and amplitude of the first Empirical Orthogonal Function of temperature profile database in the East Sea (KORDI 1991).

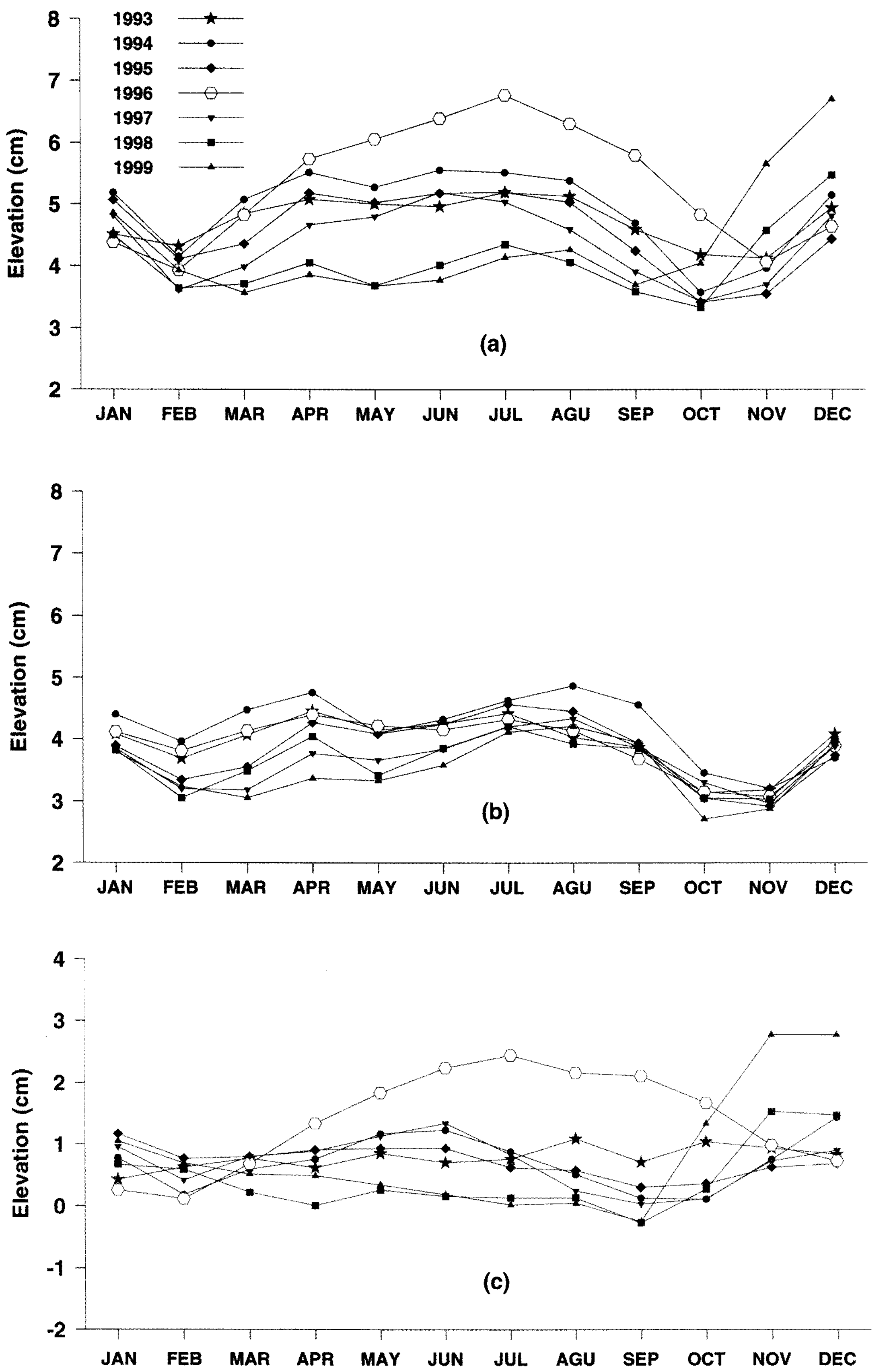

Fig. 3. The time series of root-mean square of mean elevation over the entire East Sea for (a) the MCSST-only case, (b) data assimilation case, and (c) the difference between the two cases.

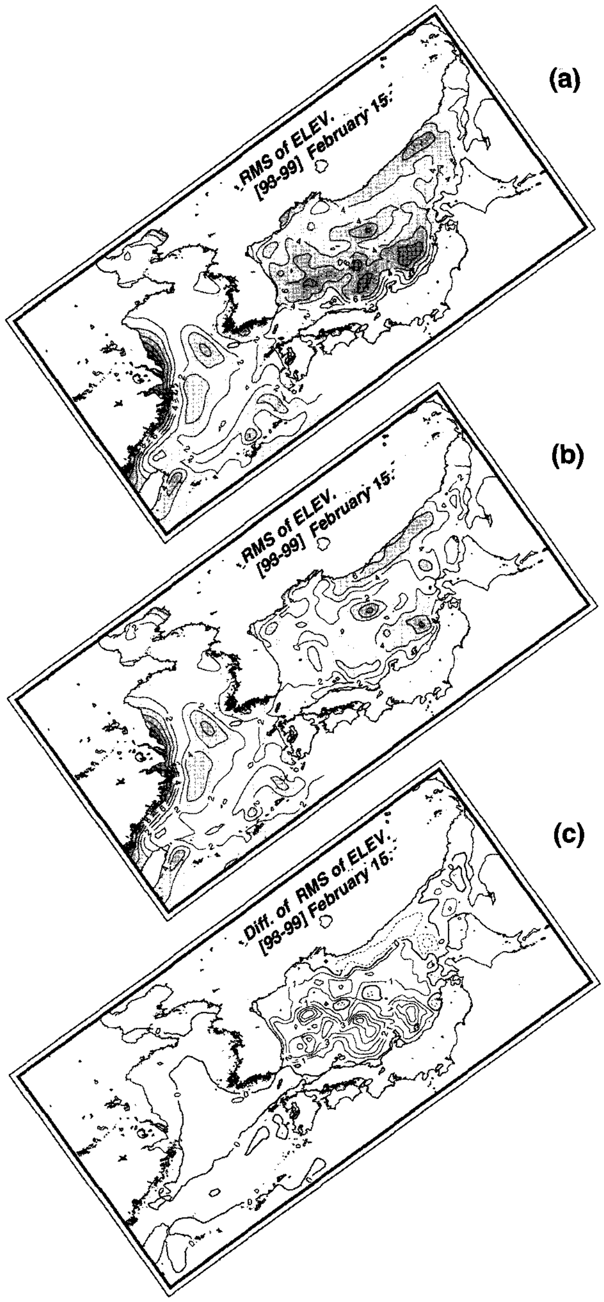

Fig. 4. Spatial distribution of the root-mean-square elevation in February for (a) the data assimilation case, (b) MCSST-only case, and (c) the difference between the two cases.

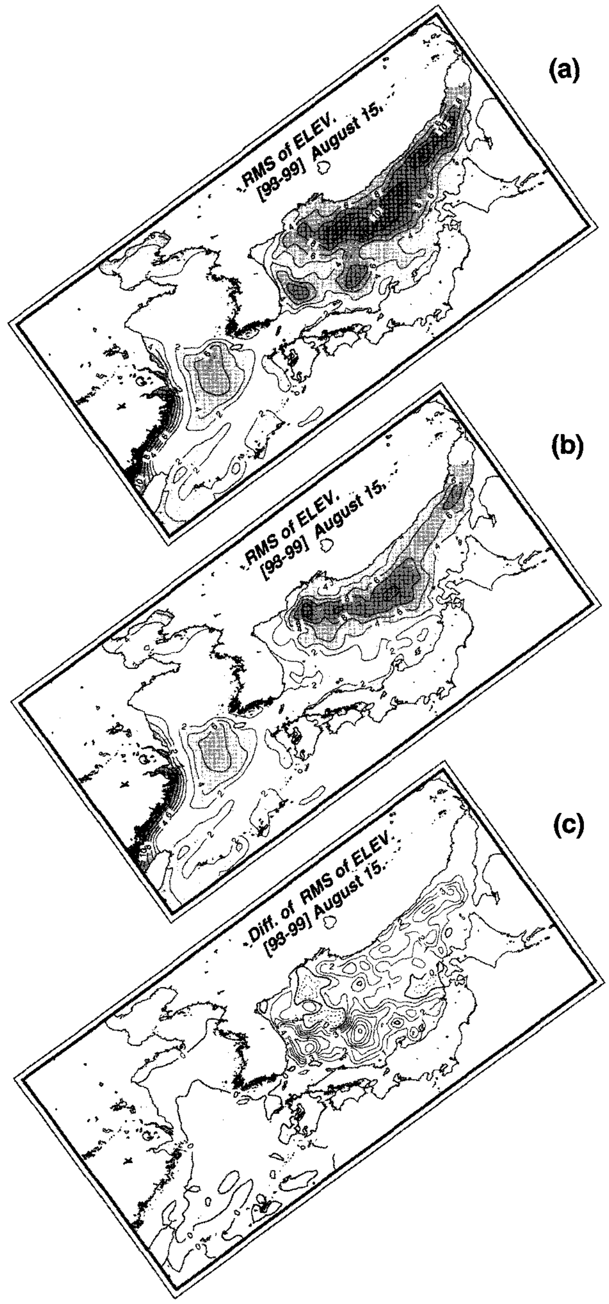

Fig. 5. Spatial distribution of the root-mean-square elevation in August for (a) the data assimilation case, (b) MCSST-only case, and (c) the difference between the two cases.

4. Results and discussion

The annual cycle of the sea-surface elevation has been well reproduced by the KC model run for 7 years with the climatological forcing. Two branches of the surface currents are clearly shown in the East Sea; one is the East Korea Warm Current flowing northwards along the Korean coasts, and the other is the nearshore branch along the Japanese coasts (not shown). There is a cyclonic gyre as a whole over the Japan Basin in the northern part of the East Sea, and the Liman Current flowing southwards along the Syberian coast forming the western boundary current of the cyclonic gyre. The fluctuation of the polar front crossing the middle of the basin causes the flow pattern to change throughout the whole basin. In addition, it is clearly noticed that the warm rings appear to the south of the polar front over the Ulleung and the Yamato Basins all around the year.

Initializing with the three-dimensional results of the last day of the 7-year long experiment with the climatological forcing, we ran the KC model for 1990~1999 with MCSST forcing (referred to as MCSST-only case hereafter). At the beginning of 1993 we ran another case with RSSH data assimilation (referred to as data assimilation case hereafter) applied only in the East Sea. The total root-mean-square (referred to as RMS hereafter) elevation for 1993~1999 from the MCSST-only and the data assimilation cases are shown in Fig. 3. In both cases seasonal and year- to-year variability are quite large. For the data assimilation case, the total RMS elevation becomes larger by about 1.5 times as compared to the MCSST-only case. This increase in RMS elevation appears to be associated with an increase in mesoscale features for the data assimilation case.

Spatial distributions of the RMS elevation in February and August are shown in Figs. 4 and 5, respectively. The model run for the MCSST-only case shows higher variability near the Russian coast in August (Fig. 5(c)) as compared to the data assimilation case. Otherwise the experiment with the data assimilation shows higher variability than those without the assimilation both in February (Fig. 4) and August (Fig. 5) over the entire East Sea. The difference between the MCSST-only and the data assimilation cases is lager to the south of the polar front than to the north of the front.

High variability occurs in the region where mesoscale features such as eddies and frontal fluctuation are found. More complicated features are realized in the data assimilation case than that of MCSST-only case, which is also expected from the comparison of total RMS elevation between the two experiments. The short-term and seasonal variability is confined mostly to the upper 100-150 m. The interannual variability is noticeable in the data assimilation model as compared to that in the MCSST-only case (Fig. 3). Physical processes for these features are complex and can generally be associated with surface wind stress, surface thermohaline fluxes and concomitant water mass formation in the northern East Sea, inflow/outflow across the straits, and topographic control.

Many of the commonly identified and documented mesoscale circulation features can be clearly seen especially in the East Sea. While overall pictures of the circulation in the entire Korean waters appears to be reasonable, the model results needs to be more carefully examined. Sensitivity tests are also required for the assessment of effects of boundary conditions and forcing, and subgrid scale parameterization on simulated results. Future works will also include refining the spatial grid resolution and incorporating numerical weather prediction products for the use of the modeling system as an operational prediction tool.

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