O2-1. Application of the Ensemble Kalman Filter to the Kuroshio variation south of Japan

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Abstract: We investigated the feasibility of the Ensemble Kalman Filter (EnKF) to reproduce the Kuroshio variation south of Japan. We have adopted the Local Ensemble Transformation Kalman Filter (LETKF) algorithm based on 20 ensemble members of the parallelized Princeton Ocean Model (sbPOM) with horizontal resolution of 1/36 degree. By assimilating satellite sea surface height anomaly, satellite sea surface temperature, and in-situ temperature and salinity profiles, we reproduced the Kuroshio variation south of Japan for the period from 8 to 28 February 2010. EnKF successfully reproduced the Kuroshio path positions and the water mass property of the Kuroshio waters as observed. Variation of the thermohaline front in the winter Kii Channel, 'Kii Channel Front', due to the intrusion of the Kuroshio water toward the channel was clearly detected by the assimilation, suggesting the effectiveness of flow-dependent error covariance represented by EnKF.

Keywords: Ensemble Kalman Filter (EnKF), Kuroshio south of Japan, Kii Channel Front, open-sea and coastal interactions.

1. INTRODUCTION

Variability of geophysical systems is highly chaotic [3]. An ultimate goal of geophysical predictability studies is exact evaluation of probability distributions associated with target phenomena. The Ensemble Kalman Filter (EnKF, [1]) allows dynamic evaluation of two important moments of probability distribution: mean and error covariance, with some accuracy. There have been no studies to use EnKF for analysis of the Kuroshio variations south of Japan in spite of their complicated spatiotemporal variability. Other types of data assimilation methods that have been frequently used for operational applications to the Kuroshio variations: optimum interpolation [5,6] and three-dimensional variational method [7] assumed temporally constant and spatially isotropic error covariance. Main target phenomena of the previous studies were the typical mesoscale phenomena such as the Kuroshio path variation and mesoscale eddies with O(100km) and O(10days) scales. Recent development of downscaled models allows to simulate smaller scales phenomena [4]. Dynamic representation of error covariance by EnKF is required to effectively reproduce the smaller scales phenomena based on the available observation data. This study aims to elucidate the feasibility of EnKF for the analysis of the Kuroshio variations south of Japan, especially focusing on roles of error covariance information in representation of the Kuroshio and coastal sea interactions [10,11].

2. ENSEMBLE KALMAN FILTER SYSTEM

2.1 Ocean model

We have developed an ocean model for south of Japan based on a parallelized version of the Princeton Ocean Model (Stony Brook Parallel Ocean Model; sbPOM, available from http://www.imedea.uib-csic.es/users/toni/sbpom/). The model covers a square region of 31°-35°N and 133°-140°E with the horizontal grid of 1/36 degree and 31 sigma levels. The bottom topography of the model was created from 1/120 degree grid data, JTOPO30, provided by Japan Hydrographic Association. The model was driven by wind and heat fluxes calculated using atmospheric variables provided from the NCEP Global Forecast System. The surface salt flux was relaxed to surface salinity of the monthly mean climatology, World Ocean Atlas. The lateral boundary condition was specified from the JAMSTEC operational ocean model product with the same horizontal resolution of 1/36 degree [4], which assimilated satellite sea surface height anomaly data using a three-dimensional variational method [7]. The model was spun up for the period from November 2008 to November 2010 starting from temperature and salinity data of the JAMSTEC operational model with no motion.

Table 1: LETKF parameters

Horizontal localization scale (grids)	12
Vertical localization scale (m)	2000
Observation error of sea surface height anomaly (m)	0.2
Observation error of temperature (deg.C)	1.0
Observation error of salinity (psu)	0.1
Time window of sea surface height anomaly (days)	±4
Time window of temperature and salinity (days)	±1
Time interval of LETKF (days)	2

2.2 Ensemble Kalman Filter (EnKF)

We have implemented the Local Ensemble Transformation Kalman Filter (LETKF) [2,8] algorithm on the JAMSTEC scalar parallel processors system on the basis of SGI Altix 4700. 20 ensemble runs were produced using different initial conditions sampled from the spin-up simulation for the period from January to February 2010. LETKF assimilated satellite sea surface height anomaly (Jasons-1,2), satellite sea surface temperature (NOAA MCSST and AMSR-E), and in-situ temperature and salinity profiles (GTSPP) every 2 days during the period from 8 to 28 February 2010. Parameters of LETKF are described in Table 1. Since the LETKF analysis was conducted every 2-day, which is not so long time to lead to the typical bimodality of the Kuroshio path variations [5], it is not necessary to consider the possibility of non Gaussian type probability distributions that are not described simply using mean and error covariance.

3. REPRODUCED OCEANIC CONDITIONS SOUTH OF JAPAN IN FEBRARY 2010

3.1 Kuroshio path variation

Synthetic sea surface temperature maps provided by some local fishery agencies indicate that the small Kuroshio meander around 33°N and 138°E observed on 14 February 2010 moved eastward to 139°E on 20 -26 February (top panels of Fig.1). EnKF reasonably reproduced this features as shown in bottom panels of Fig.1. We compared the reproduced Kuroshio path potions, which were defined as the grid positions of strongest kinetic energy at 200m depth, with the observed positions reported by the Japan Coast Guard. Root mean square deviation (RMSD) between them was 0.27 degree for the target period.

3.2 Water mass property

To confirm fitting to the in-situ data of the assimilation products, we plotted in left (right) panel of Fig.2 the in-situ observation points with colours indicating RMSD between the reproduced and observed vertical temperature (salinity) profiles. EnKF well reproduced the observed water mass in open ocean with RMSD smaller than 1 deg.C and 0.1 psu, which are the prescribed observation error values (Table 1). Comparatively large RMSD values indicated by red colour points are shown near the coast, especially in the Kii Channel existing the Shikoku Island (see 'S' in bottom left panel of Fig.1) and Kii Peninsula (see 'K' in bottom left panel of Fig.1). Ensemble subsurface temperature spread plotted in background of left panel of Fig.2 exhibits that large magnitude of the spread is distributed along the Kuroshio path and in the Kii Channel. Large values of salinity spread are shown in the coastal seas including the Kii Channel. Approximate correspondence between the regions showing large deviations of fitting to the in-situ data and large magnitude of the spread suggests that the ensemble spread is a qualitative indication of unknown errors contained in the reproduced oceanic conditions. Mean deviation (bias) of the reproduced profiles to those observed indicates that too high (low) subsurface temperature and salinity values are reproduced inside (outside) of the Kii Channel (not shown). This kind of mismatch is possible because the real horizontal gradient of the winter front between the warm Kuroshio and cold coastal waters in the Kii Channel is too sharp, usually exceeding 5 deg.C/km [11], to represent it using the horizontal resolution of 1/36 degree (2-3km).

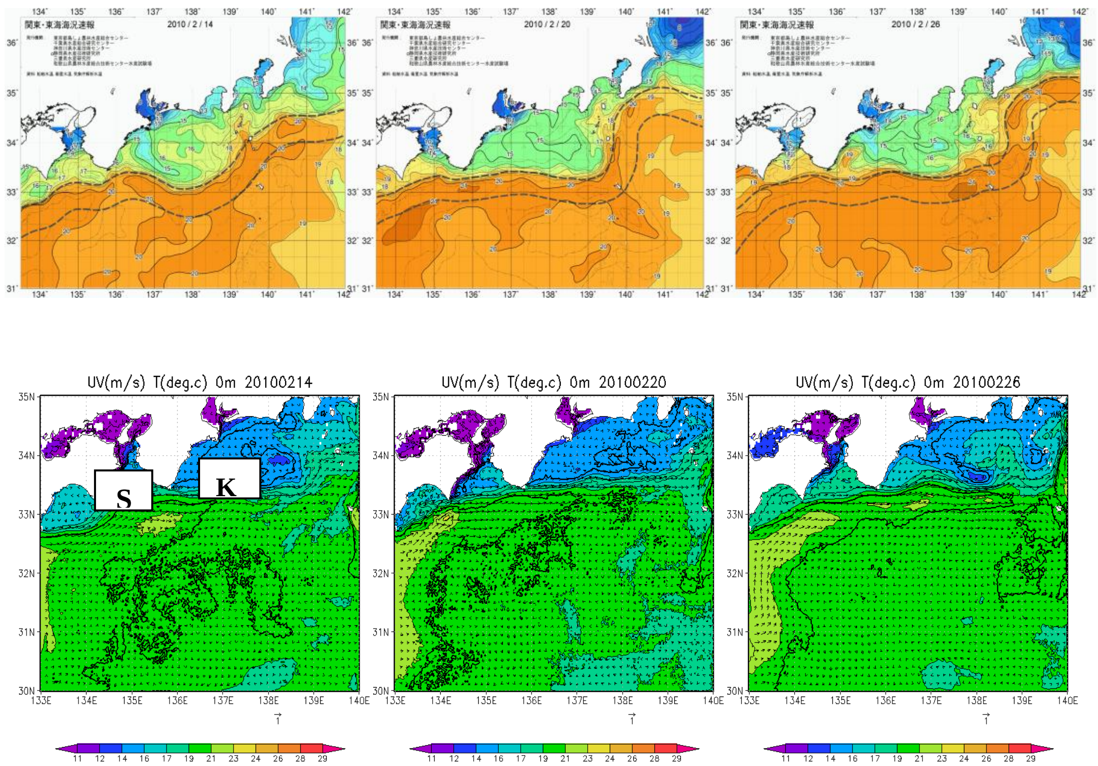

Fig. 1: Upper: Time sequences of daily synthetic sea surface temperature maps provided by the local fishery research agencies. Dashed contours indicate the Kuroshio. Lower: EnKF analyses mean of sea surface temperature (shade) and current (vectors). Thick contours indicates temperature with interval of 5 deg.C. 'S' and 'K' shown in left panel denote the Shikoku Island and Kii Peninsula, respectively.

3.3 Variation of the Kii Front Channel

Despite the comparatively large deviation of the reproduced water mass property from that observed in the Kii Channel (Fig.2), EnKF represented some observed front variation in the Kii Channel. On 14 February, the Kuroshio front was a little bit far from the Kii Channel, where the well known S-shape coastal front [11] was formed (left panels of Fig.1). The EnKF snapshots indicated that the Kuroshio front moved northward and the warm water intruded toward the channel along the west coast of the Kii Peninsula (bottom middle panel of Fig.1). This event is similar to the warm water intrusion through the 'Kinan Branch' [10]. The synthetic observation maps suggest the different front variation; the cold water as a western part of the S-shape front seemed to disappear on 20 February (top middle panel), but EnKF reproduced the south-westward intrusion of the cold water (bottom middle panel), suggesting the intensification of the S-shape front. Both of the observation and EnKF snapshots on 26 February indicate the northward intrusion of the warm water toward the inside of the channel (right panels).

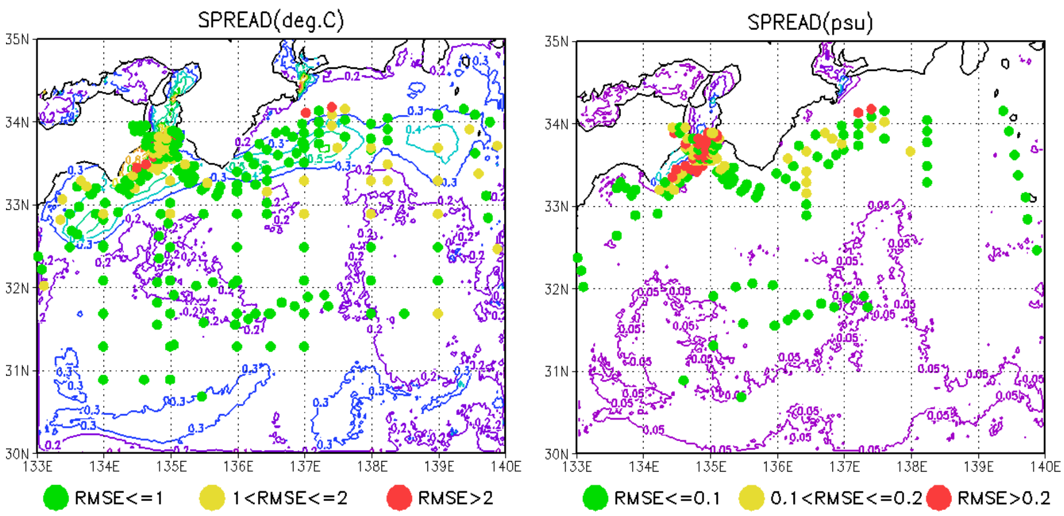

Fig. 2: Left: maximum analysis ensemble spread of temperature from surface to bottom averaged for the period from 8 to 28 February 2010. Closed circles denote positions of the in-situ temperature observations and colour indicates Root Mean Square Deviation between the reproduced and observed temperature profiles. Right: same as left panel except for salinity.

The representation of the warm water intrusion along the west coast of the Kii Peninsula, the 'Kinan Branch', was enhanced by the assimilation of the in-situ profile data. Left panel of Fig.3 shows that the in-situ observation data points on 18 February were found in the Kii Channel. Using information of the ensemble spread, we can evaluate impacts of the in-situ data assimilation. Impact Signal (IS) [9] of the assimilation is defined as,

$$IS \equiv \begin{cases} \bar{x}_w - \bar{x}_{w/o} & if \ \left|\bar{x}_w - \bar{x}_{w/o}\right| \Big/ \sqrt{(Spread_w{}^2 + Spread_{w/o}{}^2)/(K-1)} > t_{95\%} \\ 0 & not \end{cases} ,$$

where $\bar{x}_w - \bar{x}_{w/o}$ is difference of variables between with (w) and without (w/o) the assimilation of some observation data, K is ensemble size (=20), and $t_{95\%}$ is a critical t-distribution value of 95 % significance with K-1 degree of freedom. IS of sea surface temperature between with and without the assimilation of the in-situ temperature and salinity profiles on 18 February is plotted in right panel of Fig.3. Positive (negative) anomaly is found along the west coast of the Kii Peninsula (inside of the Kii Channel), indicating that the in-situ data assimilation enhanced the intensity of the Kii Channel Front. This enhancement suggests that flow dependent error covariance (not shown) represented by EnKF modified the front without any kind of smoothing it. Isotropic and time constant error covariance, which is frequently used in the other types of data assimilation methods: optimum interpolation and three-dimensional variational method etc., may smooth the horizontal gradient of the front in this case. Other positive impact signal around 33.3°N and 135.4°E comes from the downstream in-situ observation at 33°N and 135°E, also suggesting the effect of the flow dependent covariance (not shown) that represents the advection along the Kuroshio main axis.

4. CONCLUSIONS

This study demonstrates the feasibility of the Ensemble Kalman Filter (EnKF) to the investigation of the real Kuroshio variation south of Japan in February 2010. EnKF well reproduced the Kuroshio path positions with Root Mean Square Deviation (RMSD) to the observation of 0.27 deg., which is better skill than that of the three-dimensional variational method, 0.33 deg. Also, EnKF well reproduced the observed water mass property in the Kuroshio region with RMSD of temperature and salinity smaller than 1 deg.C and 0.1 psu, respectively. It was found that EnKF effectively assimilated the in-situ temperature and salinity data to represent the sharp structure of the Kii Channel Front and its variation affected by the warm water intrusion from the Kuroshio region, suggesting the efficiency of EnKF for detection of open-sea and coastal interactions with highly complicated spatiotemporal variability.

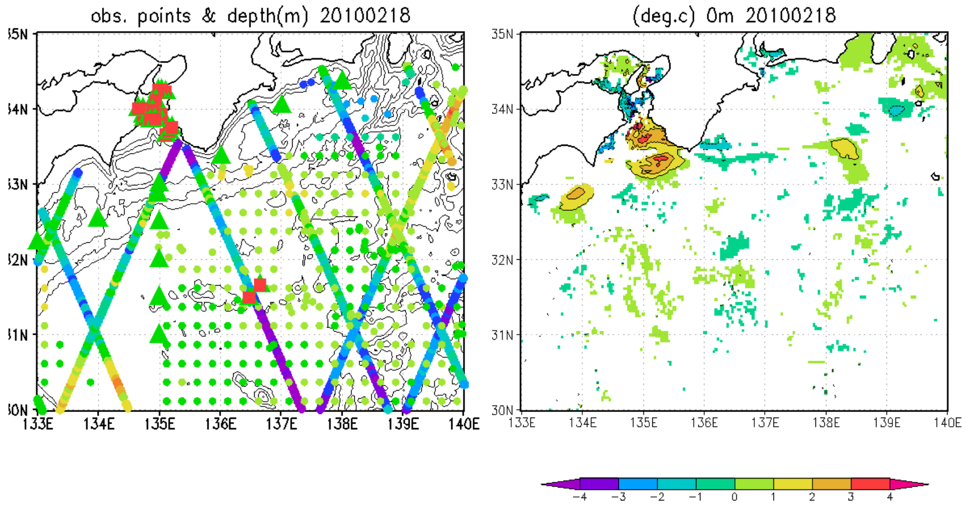

Fig.3: Left: positions of the assimilated observation data on 18 February 2010. Lines, closed circles, closed triangles, and closed squares denote satellite sea surface height anomaly, satellite sea surface temperature, in-situ temperature, and in-situ salinity observations, respectively. Contours indicate iso-depth lines. Right: Impact Signal (IS) of sea surface temperature for the in-situ temperature and salinity data assimilation on 18 February 2010.

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