Sensitivity study for prediction experiments of Northwestern Pacific Ocean based on an ensemble four-dimensional variational method

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1. Introduction

At the present time, December 2024, Kuroshio path south of Japan takes the large meander state and it has continued since August 2017. We experience an anomalously long 7-year period of the large meander condition. Furthermore, the Kuroshio separating from the nearshore region of the Japan coast has taken an anomalous northward extension path since 2023, though usually the Kuroshio Extension flows eastward east of Japan. Those anomalous conditions seriously affect the fishery activities off Tohoku region through significant warming of the oceanic state from surface to subsurface layers. To understand the maintenance mechanisms of such Kuroshio extreme phenomena and examine predictability of the variability in 2-month lead time from initialization of the oceanic states, we have constructed an ensemble forecast system targeting the Northwestern Pacific Ocean based on an ensemble four-dimensional variational (En4dVar) data assimilation, as a part of a Earth Simulator (ES) project entitled with 'High-performance computing of ocean models for Japan Coastal Ocean Predictability Experiment (JCOPE)'. From summer of 2023, we have repeated near-real time forecast experiments using ES with an interval of 8-day. During the courses of the forecast operations, we have found sensitivity of some parameters in both model and data assimilation (DA) systems. Here we report the results of the detected parameters sensitivity.

2. JCOPE-T Northwestern Pacific model

An ocean general circulation model JCOPE-T is used for the oceanic state simulations. The model horizontally covers 10. 5◦-62◦N and 108◦-180◦E with a resolution of 1/12◦ (approximately 9-km), and includes 46 active vertical layers based on a generalized sigma coordinate with a maximum depth of 6500 m. The Northwestern Pacific model component is nested in a coarser-grid (approximately 1/4◦ resolution and 20 layers) North Pacific model of JCOPE-T covering 30◦S to 62◦N and 100◦E to 90◦W. The lateral boundary of the outer model is no inflow allowing outflow from inside assuming a radiation condition with temperature/salinity climatology (World Ocean Atlas 2001 (WOA01)).

The coarser-grid North Pacific model was spun up from 1986 to 2024 from the motionless state and WOA01 temperature/salinity. The finer-resolution Northwestern Pacific model was spun up for the same period from the same initial conditions with one-way nesting by the lower-resolution model.

The atmospheric forcing at sea surface is generated using bulk formulae with atmospheric variables provided from both past analysis and seasonal forecast of National Centers for Environmental Prediction Climate Forecast System Version 2 (NCEP-CFSv2). Freshwater flux is applied at the sea surface to represent the effects of precipitation and evaporation.

The freshwater flux caused by the discharge of small rivers is represented as the enhanced precipitation along the coasts over a strip of land 80 km wide in the Northwestern Pacific model. The climatological monthly freshwater volume flux from the two large rivers alone, Changjiang and Amur, is represented in the model by the freshwater volume fluxes in the grid cells located at the river mouths.

3. Adjoint-free 4dVar data assimilation system

An ensemble-based forecast system (JCOPE-a4dvar) has been implemented using the adjoint-free 4dVar (a4dVar) method [1]. JCOPE-a4dVar generates a 22-member ensemble from the first guess initial condition produced by the multiscale 3dVar (ms3dVar) DA method. Both a4dVar and ms3dVar assimilate the synthetic merged sea surface temperature data (MGDSST) and the along-track sea surface height anomaly SSHA (Ssalto/Duacs altimeter products) . The ms3dVar system additionally assimilates high-resolution satellite sea surface temperature (Himawari-8) and in situ temperature-salinity profile data (Global Temperature and Salinity Profile Programme (GTSPP)). The a4dVar algorithm is designed for mainly extracting the time-dependent information on the oceanic variability from SSHA observations during the DA window. The length of the DA window is 10 days. All SSHA data within the DA window are assimilated daily whereas MGDSST data are assimilated only at the time of the initialization.

4. Modification of default parameters

We have started near-real time experiments from the end of June 2023. However, the initial forecast results sometimes showed that the cold eddy of the Kuroshio meander core south of Japan and the warm eddy related to the northward extension of the Kuroshio east of Japan tended to detach easily from the Kuroshio main stream.

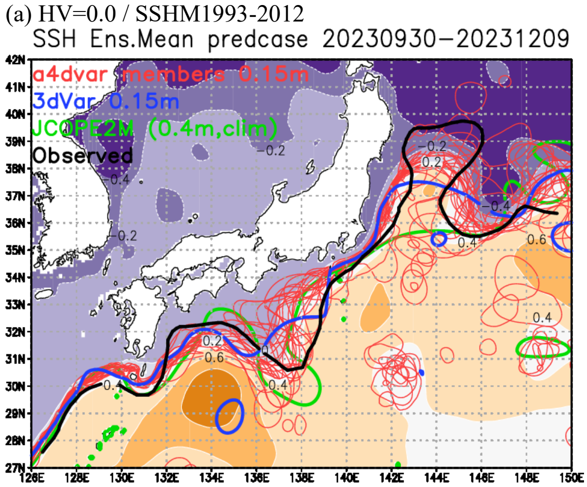
To mitigate the unstable behaviors of the predicted Kuroshio extremes, which were different from the real states of the observed Kuroshio, we have examined sensitivity of several parameters in both model and DA components. Table 1 summarizes the adjusted parameters fixed after a number of trials.

Table 1. Adjusted parameters (default parameters)

a) Multiplying constant of wind stress magnitude
1.1 (1.0)
b) The Smagorinsky constant for harmonic viscosity (HV)
0.7 (0.0)
c) The Smagorinsky constant of biharmonic viscosity
0.1 (0.1)
d) Current feedback parameterization
ON (OFF)
e) Bottom roughness parameterization
ON (OFF)
f) Period of mean SSH (SSHM) for evaluation of model SSHA
1993-2022 (1993-2012)

We briefly describe adjustment of the targeted parameters shown in Table 1 as follows: a) since preliminary simulation experiments indicate slightly lower values of the Kuroshio transport across the PN line around Amami Island and 137°E line south of Japan, we have slightly intensified the wind stress magnitude by multiplying default values by 1.1., b) we have introduced a hybrid viscosity scheme to mitigate unrealistically intensified meandering behaviors by adding the harmonic operator to the default setting of biharmonic viscosity operator, c) Adjustment of biharmonic viscosity operator shows unclarified responses depending on the initial conditions, and finally we have decided to keep a default value, d) Default setting of the wind stress formulation simply assumes that wind velocities relative to surface ocean current velocities are included in the bulk formulae; however, it tends to underestimate both the mean and eddy components of ocean currents, so we have introduced a parameterization representing ocean current feedback to wind, which are reasonably simulated in atmosphere-ocean couple modeling, e) To compensate possibly underestimated bottom friction in the bottom-following coordinate, we have introduced a parameterization of bottom roughness using a high-resolution (0.5km resolution) SRTM15 topography data product, f) The a4dVar process requires a mean SSH filed to evaluate model SSHA for assimilating observed SSHA, and we found predicted both relatively weak Kuroshio large meander core and Kuroshio northward extension in a case of mean SSH period for 1993-2012 in comparison with a case of period for 1993-2022.

(a) HV=0.0 / SSHM1993-2012



(b) HV=0.7 / SSHM1993-2022

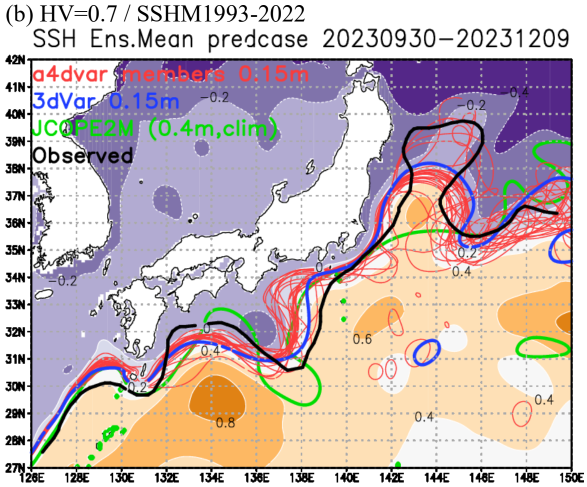


Figure 1. Sea surface height (SSH) of ensemble mean forecast (shade) 2-month after the a4dVar initialization. Red (blue) contours denote locations of 0.15m SSH levels in the a4dVar ensemble (ms3dVar) forecasts. Green contours denote those of 0.4m in a previous version of the ocean forecast system JCOPE2M. Black contours show locations of observed Kuroshio axis reported from the Japan Coast Guard.

Figure 1 compares snapshots of 2-month lead forecast SSH in a case of a) HV=0.0 and SSHM 1993-2012, and b) HV=0.7 and SSHM 1993-2022. The present choice of the parameters reasonably exhibits both stable Kuroshio large meander south of Japan and northward extension of the Kuroshio east of Japan. Requirement of additional harmonic viscosity for stabilization of the Kuroshio path variability strongly suggests remaining missing processes related to kinetic energy dissipation of ocean currents in the current design of the ocean model including resolution, parameterization, numerical schemes, etc. Using the adjusted forecast system, we will examine the predictability of the Kuroshio extreme phenomena and further investigate their underlying dynamics.

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References

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