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Model-based assessment of a Northwestern Tropical Pacific moored array to monitor intraseasonal variability

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ABSTRACT

The Northwestern Tropical Pacific Ocean (NWTPO) moorings observing system, including 15 moorings, was established in 2013 to provide velocity profile data. Observing system simulation experiments (OSSEs) were carried out to assess the ability of the observation system to monitor intraseasonal variability in a pilot study, where ideal "mooring-observed" velocity was assimilated using Ensemble Optimal Interpolation (EnOI) based on the Regional Oceanic Modeling System (ROMS). Because errors between the control and "nature" runs have a mesoscale structure, a random ensemble derived from 20–90-day bandpass-filtered nine-year model outputs is proved to be more appropriate for the NWTPO mooring array assimilation than a random ensemble derived from a 30-day running mean. The simulation of the intraseasonal currents in the North Equatorial Current (NEC), North Equatorial Countercurrent (NECC), and Equatorial Undercurrent (EUC) areas can be improved by assimilating velocity profiles using a 20–90-day bandpass-filtered ensemble. The root mean square errors (RMSEs) of the intraseasonal zonal (U) and meridional velocity (V) above 500 m depth within the study area (between 0°N–18°N and 122°E–147°E) were reduced by 15.4% and 16.9%, respectively. Improvements in the downstream area of the NEC moorings transect were optimum where the RMSEs of the intraseasonal velocities above 500 m were reduced by more than 30%. Assimilating velocity profiles can have a positive impact on the simulation and forecast of thermohaline structure and sea level anomalies in the ocean.

1. Introduction

The Northwestern Tropical Pacific Ocean (NWTPO) circulation system impacts the ocean heat balance and ocean–atmosphere interaction in the Western Pacific Warm Pool, and affects ENSO cycles and the global climate system (Webster and Lukas, 1992). The NWTPO is where water masses from middle to high latitudes intersect and is the source region for the Indonesian through flow, and therefore has a significant impact on the global thermohaline circulation (Gordon, 1986; Fine et al., 1994). Upper circulation in the NWTPO is characterized by alternating zonal currents (Fig. 1). The westward-flowing North Equatorial Current (NEC) is located between 9°N and 18°N and bifurcates at the Philippine coast into the poleward Kuroshio Current (KC) and equatorward Mindanao Current (MC) (Qiu and Lukas, 1996). Part of the MC turns eastward and feeds the eastward-flowing North Equatorial Countercurrent (NECC) between 3°N and 8°N (Yu et al., 2000). The lower depth boundary of the NECC is stable at 200 m, as measured by a previous study (Wang et al., 2016b). South of the NECC, there is the broad westward-flowing South Equatorial Current (SEC), part of which turns northward and also feeds into the NECC when it reaches the western boundary (Reid, 1986). At depths of 200–400 m (Fig. 1b), convergence of the MC and New Guinea Coastal Undercurrent (NGCUC) near the equator feeds the eastward-flowing Equatorial Undercurrent (EUC), and the core of the EUC lies between 200–300 m (Johnson et al., 2002; Wang et al., 2016b).

Variability of the NWTPO upper circulation system is quite strong and complex, at intraseasonal, seasonal, interannual, and longer timescales (Qiu and Joyce, 1992; Johnston and Merrifield, 2000; Qiu and Chen, 2010; Hsin and Qiu, 2012; Wu, 2013; Chen and Qiu, 2004; Xiao et al., 2017). There is a great deal of uncertainty in the simulation/forecasting of the NWTPO circulation system. The impacts of the different observation methods on seasonal–interannual forecasting variability in the tropical upper Pacific have been well assessed in the past (Smith and Meyers, 1996; Fischer et al., 1997; Parent et al., 2003; Yan et al., 2007). The different methods have included expendable bathythermo-graphs (XBT), international Tropical Ocean and Global

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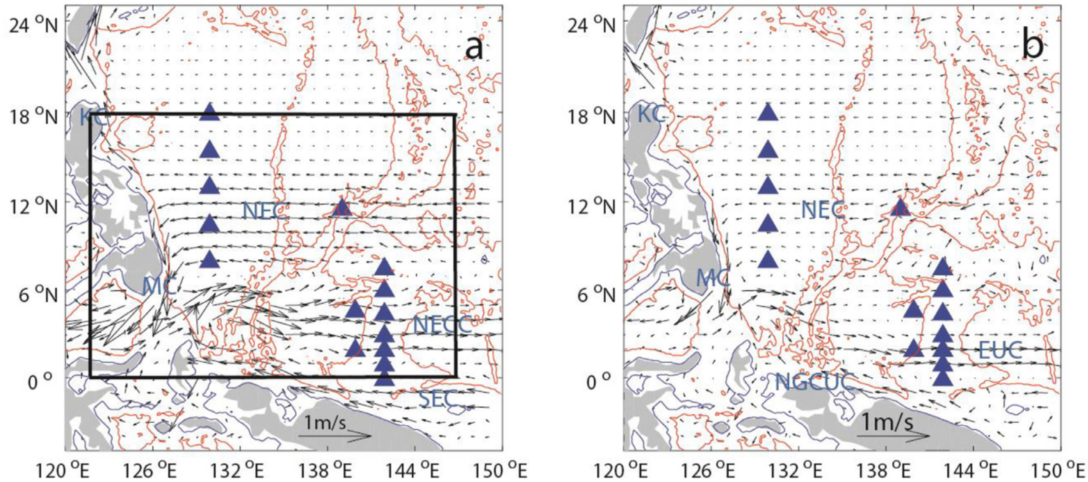

Fig. 1. The vertical-averaged circulation from ROMS data during 2000–2008. Data from 0 m to 200 m (a). Data from 200 m to 400 m (b). Blue triangles denote the locations of the NWTPO moorings. Bathymetry is shown in color: blue contours indicate 200 m isobaths and red contours indicate 4000 m isobaths. The area in the black box (0°–18°N, 122°E–147°E) is used for the following analysis. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Atmosphere/Tropical Atmosphere Ocean (TOGA/TAO) arrays, satellite observations, and the Array for Real-time Geostrophic Oceanography (Argo). The current ocean model, combined with existing observational networks in the NWTPO, can mainly resolve seasonal to interannual forecasting signals and simulate the dominant circulation on a large spatial scale (Balmaseda and Anderson, 2009; Fujii et al., 2015; Zheng and Zhu, 2016). However, traditional observing systems are still insufficient to monitor the upper intraseasonal activities in the NWTPO, especially in chaotic and turbulent areas (Oke et al., 2015). Considering that the intraseasonal anomalies of the current in the upper NWTPO are pronounced compared to the magnitude of the seasonal-mean flow, and intraseasonal variability can play a role in the NWTPO heat and tracer budget (Wang et al., 2016a), it is also necessary to improve intraseasonal simulation of the NWTPO.

As an important supplement to the NWTPO and global ocean observation system, the NWTPO moorings observation system supported by the "Western Pacific Ocean System: Structure, Dynamics and Consequences, WPOS" project, was established in 2013. This observation system contains fifteen moorings with upward and downward-looking Acoustic Doppler Current Profilers (ADCP) deployed at 400 m depth at each mooring (Fig. 1). Five of the moorings, located along 130°E, were deployed to observe NEC variability, and seven moorings were deployed across the NECC and EUC, along the 142°E transect. The other three moorings were deployed in the NEC (139.05°E, 11.58°N), NECC (140°E, 4.7°N), and EUC (140°E, 2°N). Compared to traditional observing systems, which are indirect measurements of the current, the NWTPO moorings observing system can directly provide velocity profile observations at high temporal resolution. Therefore, it is important to explore how the new observations can improve estimations of the upper intraseasonal current processes in the NWTPO.

To improve estimations, it is not only essential that the observing systems satisfy the requirements of data assimilation (DA) systems, but also to assess if the schemes of the DA are appropriate. In this study, observing system simulation experiments (OSSEs) assimilating ideal "mooring-observed" currents are designed using Ensemble Optimal Interpolation (EnOI). Ensemble Optimal Interpolation is a multivariate DA method derived from the Ensemble Kalman Filter and widely used in eddy-resolving operational applications because of its multivariate properties and computational efficiency (Oke et al., 2008; Counillon and Bertino, 2009a,b). The ensemble members of EnOI are critical for assimilation performance, which are usually chosen from the long-term results of model integration. The assimilation efficiency depends largely on how well the ensemble can represent the background error of the system (Oke et al., 2005; Counillon and Bertino, 2009a). To make the ensemble resemble the dominant errors of the model, pseudo-information on some timescales should be eliminated or restrained. To correctly reproduce the mesoscale variability around Australia, Oke et al. (2008) used a three-day average of the model state minus the seasonal cycle of the model spin-up run to eliminate the seasonal variability. Xie and Zhu (2010) obtained a quasi-stationary ensemble that can vary with the seasons to represent flow-dependence in the seasonality term for assimilation with Argo profiles. Fu et al. (2011) found that it is necessary to remove the annual and semi-annual cycles from temperature and sea level data to avoid spurious long-range correlations in the North Sea and Baltic Sea.

The main objective of this study is to assess the capacity of the NWTPO mooring array to perform intraseasonal monitoring, using EnOI DA systems with targeted ensemble scheme.

The paper is organized as follows: Section 2 briefly describes the assimilation system and the design of the DA experiments; Section 3 evaluates the time scales of ensemble effect on "mooring-observed" current DA results; Section 4 gives the result of the "mooring-observed" current DA experiments; and Section 5 provides a summary and discussion.

2. Model, DA methods, and experiment design

2.1. Model setup and validation

Observing system simulation experiments (OSSEs) in the NWTPO were conducted using the Regional Oceanic Modeling System (ROMS) (Shchepetkin and McWilliams, 2003, 2005). The model domain spans the South China Sea and the western Pacific Ocean (15°S–35°N and 100°E–150°E). The model consists of 511 × 517 grids with an average spatial resolution of 10 km and a vertical S-coordinate designed to have 40 levels. A horizontally orthogonal coordinate system was used. The model water depth is based on the 2-min Earth topography (ETOPO2v2), and the minimum and maximum depths for the domain are set to 10 and 5,000 m, respectively. The Mellor and Yamada 2.5 level turbulent closure scheme (Mellor and Yamada, 1982) was used to parameterize the vertical mixing. A daily mean wind field from the QuikSCAT ocean surface wind product was employed, which was converted into the wind stress using the bulk formula given by Large and Pond (1982). The other daily atmospheric forcing fields, including heat fluxes, solar radiation fluxes, Evaporation–Precipitation (E–P), air temperature, and specific humidity, were obtained from the

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