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Residual Circulations and Associated Water Mass Transport in the South China Sea Analyzed with a Coupled HYCOM-ROMS Downscaling Ocean Model

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Abstract. A high-resolution, high-precision downscaling oceanic circulation model for the Southern China Sea (SCS) was developed based on the Regional Oceanic Modeling System (ROMS) at a lateral resolution of 5 km, initialized and forced by the HYbrid Coordinate Ocean Model (HYCOM) global reanalysis product. A multi-year reanalysis was conducted with the HYCOM-ROMS system that properly accounts for wind stress and heat budget at surface, freshwater influences from the atmosphere and major rivers, and tidal variability. Prospective applications of the system include assessments of oceanic dispersal of wastewater, quantification of marine ecosystem network, analyses of micro plastic transport and its coastal accumulation, etc. In prior to applied studies, we extensively investigated the validity and performance of the developed system. We found that it successfully reproduced primary dynamics of the SCS in many aspects such as the transient Kuroshio path in the south of Taiwan prominently affecting the circulation of the northern SCS through the Luzon Strait. The North Equatorial Current (NEC) drifting near Bismarck Archipelago, New Guinea, sporadically intrudes into the Indonesian water and adjacent seas to invoke bifurcating northward and westward currents. This intrusion promotes the northwestward mass transport into the Celebes Sea and further into the Sulu Sea, and then enters the SCS through the Palawan Strait.

INTRODUCTION

A precise operational oceanic reanalysis-forecast system for the South China Sea (SCS) and its surrounding sub-basins has considerably been demanded for many purposes including maintenance of platforms and rigs for mining, maritime navigations, and oceanic material dispersal responsible for aquatic ecosystems. It has been well known that the dynamics of the northern SCS is considerably affected by energetic internal waves primarily excited in the Luzon Strait (**Fig. 1**). Nevertheless, dynamics in the southern SCS is much poorly understood because of the topographic complicatedness associated with thousands of islands around Malaysia, Indonesia, and their neighbors. Challenges toward rigorous ocean circulation modeling for the SCS involve energetic internal tides and influences from oceanic western boundary currents, in particular the Kuroshio and Mindanao Current flowing on the east off the SCS. Complex coastline topography and thousands of islands introduce additional difficulty in the modeling. A solid solution to such oceanic conditions is evidently a nesting approach, where large-scale information is conveyed into the embedded high-resolution child domain through open boundaries (e.g., Mason *et al* [1]).

In the present study, we primarily aimed to develop a high-resolution, high-precision downscaling model for the SCS based on the Regional Oceanic Modeling System (ROMS, Shchepetkin and McWilliams, 2005 [2]), initialized and forced by the global HYbrid Coordinate Ocean Model (HYCOM) reanalysis conducted by the HYCOM consortium. A prototype of the proposing modeling system is the JCOPE2-ROMS system (e.g., Uchiyama *et al*., 2018 [3], 2017 [4], 2018 [5]; Tada *et al*. 2018 [6]), where the child model relies on large-scale oceanic signals

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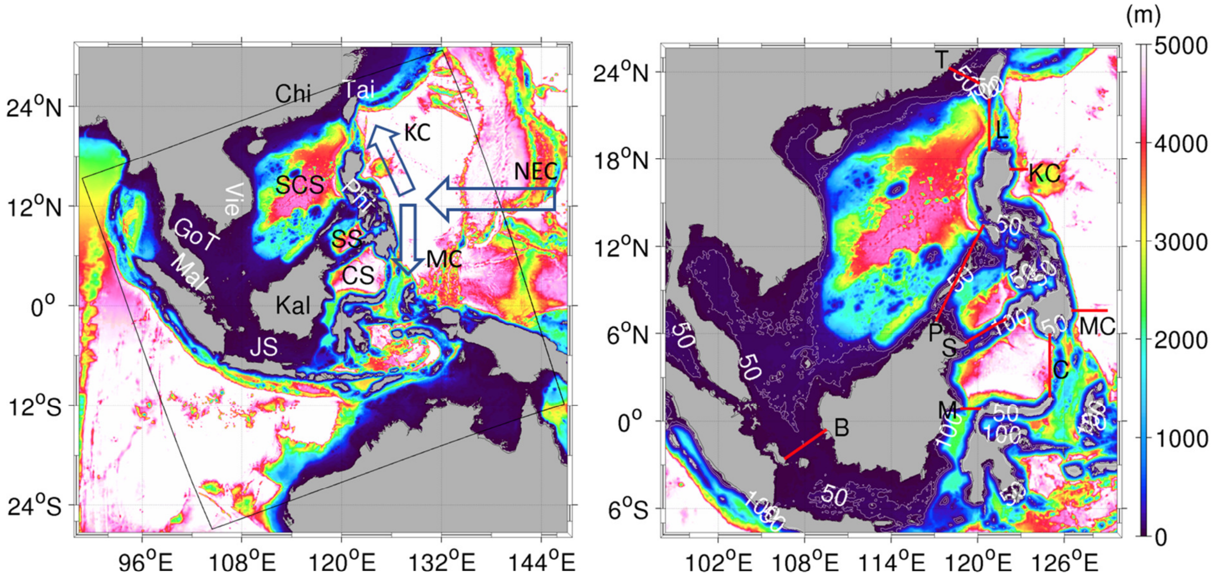

FIGURE 1. (a) Left: the study area around the South China Sea (SCS), and (b) right: its enlargement. The black rectangle in (a) is the ROMS model domain. Arrows in (a) represent three major currents, KC, MC, and NEC, which stand for the Kuroshio, the Mindanao Current, and the North Equatorial Current, respectively. Colors show the bathymetry in meter, supplemented by white thin contours for the selected shallow isobaths of 50 and 100 m in (b). Texts are acronyms of major sub-basins of the SCS: Celebes Sea (CS), Sulu Sea (SS), Java Sea (JS), and Gulf of Thailand (GoT). The red lines indicate transects surrounding the SCS, including Luzon Strait (L), Celebes Strait (C), Makassar Strait (M), Palawan Strait (P), and Bangka Island Strait (B), all of which are used in the volume flux analysis.

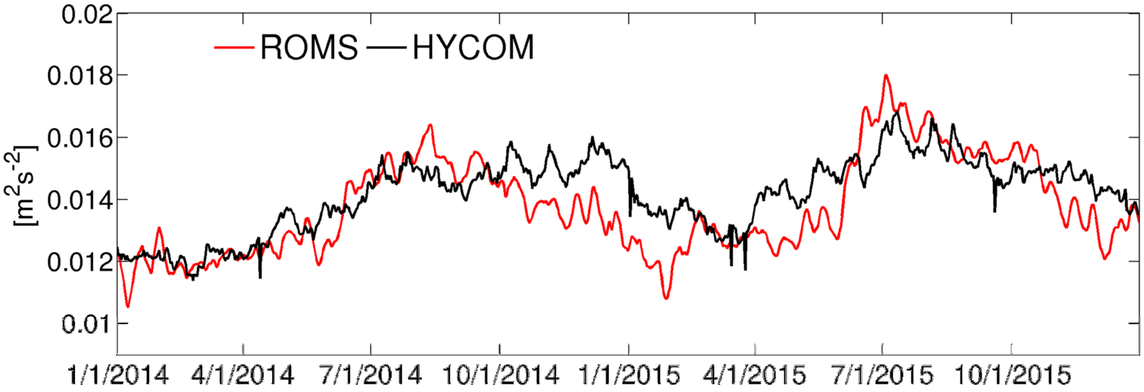

FIGURE 2. Time series of volume-averaged kinetic energy in the upper ocean from the surface down to the depth of 400 m. Red curve: ROMS, black: HYCOM.

evaluated by the assimilative JCOPE2 reanalysis (Miyazawa *et al.*, 2009 [7]). The developed HYCOM-ROMS downscaling system has a at lateral grid spacing of 5 km, which is sufficiently fine to resolve complex topography and bathymetry of the SCS, with covering not only the northern SCS but also the southern SCS including the Gulf of Thailand among others. A multi-year reanalysis was conducted using the HYCOM-ROMS system that properly accounts for wind stress and heat/freshwater budget at surface, buoyancy inputs from major rivers (e.g., Yangtze, Pearl, Mekong rivers), and tidal variability, *etc*., as accurately as possible. Then a careful model validation was carried out though extensive comparison of the model results with *in situ* measurement and satellite data to demonstrate a good reproducibility of the downscaling system. Inter- and intra-annual variability of the surface currents in the SCS is discussed in conjunction with seasonally varying surface wind stresses characterized by the

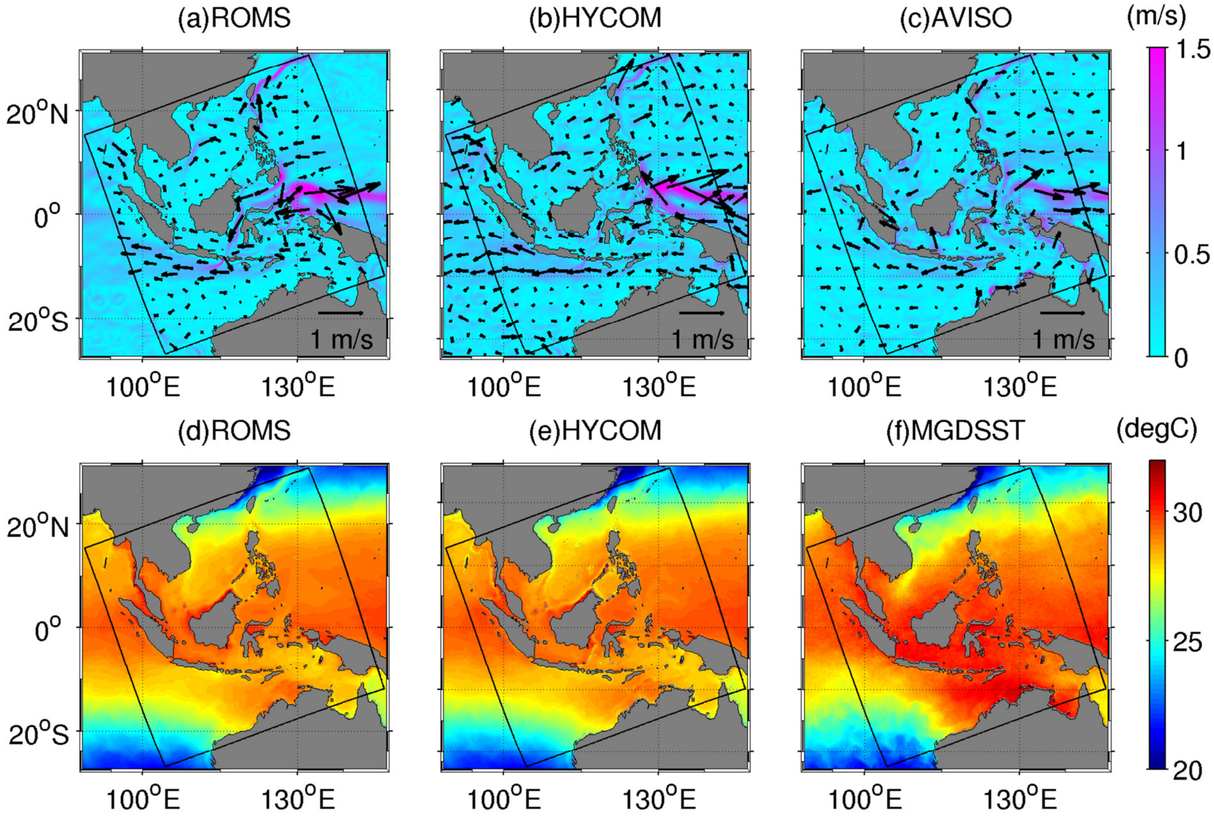

FIGURE 3. Comparisons of five year-averaged surface currents (upper panels) and sea surface temperature (SST, lower panels). From left to right, the results from the developed HYCOM-ROMS model, the assimilative HYCOM model, and satellite observations are shown. Upper: subsampled horizontal velocity vectors and their magnitudes (color, m/s). The satellite data is from the AVISO composite altimetry data. Lower: the modeled SST is water temperature of the top-most model layer, whereas the MGDSST composite data of oceanic skin temperature measured by multiple IR satellites (°C) is plotted as the observation.

winter monsoons. A fundamental, time-varying mass balance of the SCS was subsequently investigated to quantify direct and indirect influences of the Kuroshio and Mindanao Current on the SCS dynamics.

THE HYCOM-ROMS DOWNSCALING MODEL

The parent large-scale oceanic information is attained by the HYCOM + NCODA Global 1/12° assimilative product (expt 90.6–91.2) of the HYCOM consortium distributed by Center for Ocean-Atmospheric Prediction Studies (COAPS), Florida State University (https://hycom.org). The native Mercator-curvilinear HYCOM horizontal grid corresponds to ~10 km lateral resolution in mid latitudes. The daily-averaged 3-D velocity, salinity, temperature, and surface elevation were projected on to the perimeter of the child ROMS model at lateral grid resolution of ~5 km with spatial trilinear and temporal linear interpolations for the initial and open boundary conditions in an offline-nesting configuration. The embedded ROMS model was forced by the GPV-GSM, an assimilative operational global atmospheric product of the Japan Meteorological Agency (JMA), for the surface wind stresses, the global monthly climatology of the NOAA-COADS dataset for heat, freshwater, radiation fluxes at the surface, the TPXO 7.0 for global tidal constituents (e.g., Dauhajre *et al.*, 2017 [8]; Masunaga *et al.*, 2018 [9]), and the global climatological river discharge dataset of Dai *et al.* (2009) [10]. The temperature-salinity (T-S) nudging (also know as robust diagnostic; e.g., Uchiyama *et al.*, 2018 [3]) was employed to enhance the synoptic and

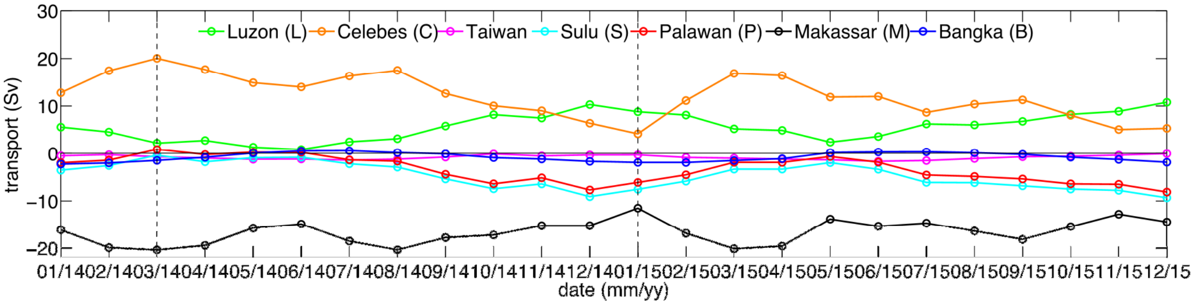

FIGURE 4. Time series plots of volume fluxes F in Sv (*n.b.*, 1 Sv = 10^6 m^3/s) at several transects defined in **Fig. 1b**. The sign is defined in such a way that positive F corresponds to incoming flux toward the SCS. A Kuroshio-originated water mass enters the SCS through the Luzon Strait (L), which is approximately in balance with the outgoing flux through the Palawan Strait (P) toward the Celebes Sea (CS) to form the SCS water. In the Celebes Sea, Mindanao water enters from the Celebes Strait (C), while SCS water enters from the Sulu Strait (S). As a consequence, both waters have to exit the CS at the Makassar Strait (M), leading to formation of through flow toward the Java Sea (JS).

mesoscale reproducibility of transient large-scale currents such as the Kuroshio. The HYCOM-ROMS reanalysis was performed for a five-year period from 2011 until 2015 excluding the first several months for the model spin-up.

MODEL VALIDATIONS

We successfully reproduced primary dynamics of the SCS in many aspects. **Figure 2** depicts time series of spatially averaged kinetic energy (= $[u^2 + v^2]/2$) in the upper ocean from the surface down to the depth of 400 m. The surface kinetic energy is viewed as a proxy of transient behavior of major oceanic currents such as the Kuroshio and associated mesoscale eddies. The assimilative HYCOM and forward ROMS models coincide each other, illustrating that the downscaled ROMS model properly reproduces the surface currents and eddies. Model-reproduced time-averaged surface currents and surface temperature (SST) distributions are also quite consistent with the satellite observations, especially in terms of patterns of the major currents and frontal structures in and around the SCS (**Fig. 3**). We have further conducted comprehensive model-data and model-model comparisons extensively, for instance on the vertical stratifications and subsurface dynamical structures (not shown). All the validations successfully demonstrate that the present HYCOM-ROMS model has a good agreement with the observed structures and their transient natures in and around the SCS.

DYNAMICS IN THE SOUTH CHINA SEA

Spatial distributions of surface currents (**Fig. 3a**) and vertically integrated volume transports (not shown) represent that the SCS is notably influenced by the offshore currents particularly two western boundary currents, the Kuroshio (KC) and Mindanao Current (MC) either in direct and indirect manners as discussed below. Both currents are originated from the North Equatorial Current (NEC), which is a part of the North Pacific Subtropical Gyre, and are bifurcated off the east coast of the Philippines to form the northward drifting KC and southward drifting MC. To quantify effects of the KC and MC on the SCS dynamics, we next conducted the volume flux analysis at several selected transect around the SCS to examine mass budget of the SCS (**Fig. 1b**). At an arbitrary transect with the cross-sectional area of A (m^2), a volume flux F (m^3/s) at a given time t is computed by

$$F(t) = \int_A u_n \, dA, \tag{1}$$

where u_n is the horizontal velocity (m/s) normal to the transect.

Figure 4 shows time series of F in Sv (*n.b.*, 1 Sv = 10^6 m^3/s) at several transects defined in **Fig. 1b**. The Kuroshio (KC) partially separates at the Luzon Strait (L) to form the westward component that leads to a remarkable inflow into the SCS from the east. On the contrary, the Mindanao Current (MC) has a pronounced remote effect on the outgoing flux from the Celebes Sea (CS) at the Celebes Strait (C). The Celebes Sea is connected with the SCS through the Sulu Sea (SS) that is fringed and surrounded by many islands. The water mass entering the Celebes Sea mainly reverts its prevailing direction toward the Java Sea (JS) via the narrow Makassar Strait (M), a part of which eventually merges with the Indonesian Through Flow to discharge out to the Indian Ocean. Therefore, the outflow from the SCS via the Celebes Sea has a relatively minor contribution to the formation of the SCS water. Nevertheless, even in an indirect way, the Mindanao Current (MC) substantially affects the SCS water because the through flux at the Celebes Strait correlates quite well with the exchanging flux between the Sulu Sea and the SCS. Moreover, the KC and MC have pronounced inter-annual and inter-seasonal variability in their intensity. Thus, enhancement and retardation of the KC and MC initiate the changes in the through fluxes at the Luzon and Celebes straits, consequently resulting in altering the mass balance and associated dynamics of the SCS significantly.

CONCLUSIONS

We developed a high-resolution HYCOM-ROMS downscaling oceanic circulation model suitable to scientific and engineering applications for the South China Sea (SCS) and its surrounding waters. The model was found to be capable of reproducing the circulations and temperature near the surface as well as the stratification in the SCS realistically. The mass budget analysis clarified that the SCS water is markedly affected both by the Kuroshio (KC) and the Mindanao Current (MC) derived from the North Equatorial Current (NEC). Because the global HYCOM does not sufficiently detect such detailed physics for its coarser grid resolution, the present high-resolution downscaling model improves representation of the regional and small-scale dynamics, which help enhance our understanding of the SCS circulations and dynamics substantially. Our next step in future work is definitely to conduct one more nesting at horizontal resolution of ~1 km, which is generally sufficient to represent submesoscale dynamics responsible for upper-ocean mixing (e.g., Kamidaira *et al*., 2018 [11]).

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