Toward an Ice–Ocean Coupled JCOPE Reanalysis System

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1. Introduction

Sea ice plays a critical role in high-latitude ocean dynamics by regulating air–sea momentum, heat, and freshwater exchanges. The presence of ice modifies surface stress, suppresses wind-driven mixing, alters upper-ocean stratification, and strongly influences circulation, water mass formation, and ecosystem processes. For operational ocean forecast systems, neglecting sea ice can therefore lead to substantial errors in surface currents, temperature, and salinity in ice-covered and seasonally ice-affected regions.

Despite these recognized impacts, the Japan Coastal Ocean Predictability Experiment (JCOPE) system developed by our group, has so far not included an explicit sea-ice component. This limitation restricts its applicability to regions such as the Sea of Okhotsk and the northern marginal seas of the North Pacific, where ice–ocean interaction is essential for realistic simulations. To address this gap, we aim to incorporate a dynamic–thermodynamic ice model developed by Fujisaki and Oey (2011), which has been successfully coupled to ocean circulation models and applied to the Sea of Okhotsk. The model represents ice momentum balance, internal ice stress, ice–air and ice–ocean drag, and thermodynamic growth and melt processes, allowing for a physically consistent treatment of ice evolution and feedback on the ocean. By integrating this ice model into JCOPE, we seek to improve the realism of ocean forecasts in ice-affected regions and to better capture coupled ice–ocean variability and its impact on circulation and air–sea interaction.

2. Method: Ice–ocean coupled model configuration

Ice–ocean interaction in this study is represented using the ice–ocean coupling module developed by Fujisaki and Oey (2011). In this framework, sea ice is treated as a continuum layer and is dynamically coupled to the underlying ocean through momentum exchange. The ice momentum equation includes Coriolis force, internal ice stress, and air–ice and ice–ocean drag, allowing ice motion to respond to both atmospheric forcing and ocean currents. Ice–ocean stress is parameterized using a quadratic drag formulation. The air–ice drag coefficient follows the formulation described in Fujisaki et al. (2010), who examined the sensitivity of ice–ocean coupled systems to variations in air–ice drag.

The ice model also includes a thermodynamic component that accounts for ice growth and melt through surface heat fluxes and oceanic heat exchange. Ice thickness and ice concentration evolve prognostically, enabling interaction between ice dynamics, ice mass balance, and ocean circulation.

The ocean circulation model used in this study is the JCOPE-MPI model (Miyazawa et al. 2024). JCOPE-MPI is based on the Princeton Ocean Model with a generalized vertical coordinate system (Mellor et al. 2002). The model domain covers the western North Pacific (10.5–62°N, 108–180°E) with a horizontal resolution of 1/12° (approximately 8–9 km) and 46 vertical layers. Surface forcing includes wind stress and net heat and freshwater fluxes derived from six-hourly atmospheric reanalysis produced by the National Centers for Environmental Prediction Climatological Forecast System Ver.2.

For the present experiment, the ice–ocean coupled model was initialized from rest using monthly climatological fields, with lateral boundary conditions provided by a coarser-resolution (~1/4º) North Pacific JCOPE model . Sea ice concentration and thickness were initially set to zero. Data assimilation was disabled to focus on the dynamical response of the coupled system. The model outputs daily mean fields, and simulations were conducted for the period from November 2011 to June 2024.

3. Result: comparison

Figure 1 compares the modeled fields (left two panels) with the ECMWF ocean reanalysis ORAS5 (right two panels) for March and April 2012. From top to bottom, the panels show sea ice concentration, sea ice thickness, sea surface temperature, sea surface salinity, and near-surface ocean currents. Overall, the model reproduces the large-scale spatial patterns seen in ORAS5 reasonably well. In particular, the extent and distribution of sea ice concentration and thickness are broadly consistent, capturing the southward advance and retreat of ice along the Okhotsk coast. The modeled surface temperature and salinity fields show similar gradients and frontal structures to the reanalysis, while the major current pathways and their seasonal changes are also well represented. These comparisons indicate that the coupled ice–ocean model is able to capture the major features of the ice and ocean state in the Sea of Okhotsk during the ice season, providing confidence for its use in the present analysis.

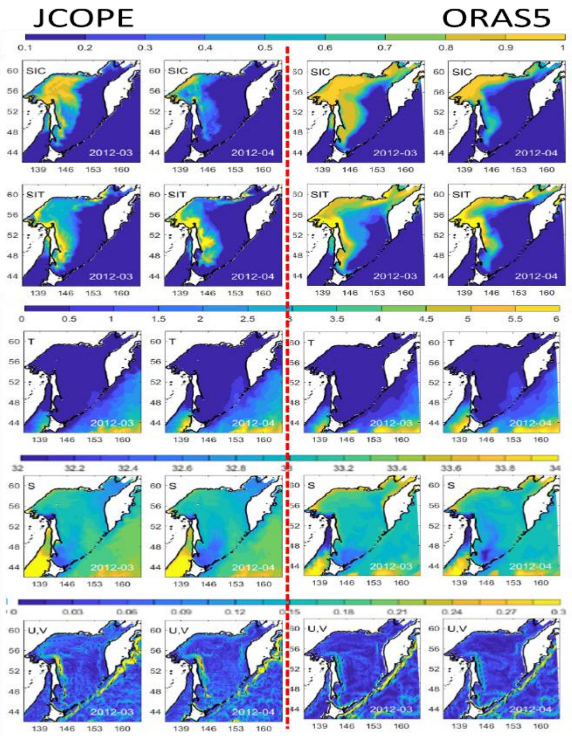

Fig. 1 Comparison between the coupled ice–ocean model results (left two panels) and the ECMWF ocean reanalysis ORAS5 (right two panels). From top to bottom, the panels show sea ice concentration, sea ice thickness, sea surface temperature, salinity, and ocean currents for Mar and Apr, 2012.

4. Result: Inter-annual variation

Figure 2 compares the simulated wintertime sea ice extent from the coupled ice–ocean model with independent observational datasets. The upper panel shows the interannual variation sea ice extent during the winter seasons from 2012 to 2023 in Sea of Okhotsk, comparing the model output with satellite-derived estimates from AMSR2. The model successfully reproduces both the magnitude and year-to-year variability of the observed ice extent, with a statistically significant correlation coefficient of $r = 0.71$ ($p = 9.0 \times 10^{-3}$). The lower panel presents a comparison of the maximum winter sea ice extent between the model and in situ estimates provided by the Japan Meteorological Agency (JMA). Agreement is particularly strong, with a high correlation of $r = 0.92$ ($p = 2.7 \times 10^{-5}$), indicating that the model captures the timing and intensity of peak ice coverage well. Overall, these results demonstrate that the coupled model realistically represents sea ice variability and provides a reliable framework for investigating ice–ocean interactions in the region.

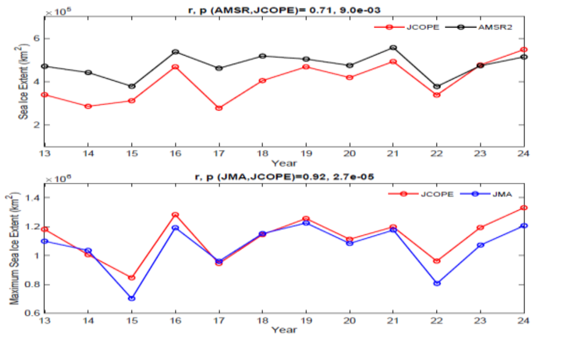

Fig. 2 Comparison of simulated and observed sea ice extent. Top: model (red) and AMSR2 (black) for 2012–2023. Bottom: model (red) and in situ observations provided by the JMA (blue).

5. Discussion and ongoing work

In the present test configuration, tidal forcing was not included in the coupled ice–ocean simulations. As a result, relatively warm Pacific water can intrude unrealistically into the Sea of Okhotsk, leading to an artificial reduction of sea ice. To mitigate this issue, TS relaxation toward monthly climatology was introduced, which effectively suppresses warm-water intrusion while retaining the dominant dynamical response to atmospheric forcing. In addition, a series of sensitivity experiments were conducted by varying key parameters. Among these tests, the parameter set adopted in the present version yielded the best overall agreement with observational datasets. To assess the robustness of the long-term simulations, additional experiments were performed with perturbed initial conditions. The resulting sea ice extent showed high similarity to the default run, indicating that the simulated ice variability is primarily controlled by external forcing. By merging the present ice module with a tide-resolving ocean model, we expect a more physically consistent representation of water mass exchange and, consequently, a more realistic simulation of sea ice variability in future applications.

Acknowledgement

The simulations were conducted using the Earth Simulator in JAMSTEC.

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