Unstructured Grid-based Seamless River-Coast-Ocean Circulation Modelling of the Seto Inland Sea

（非構造格子基盤瀬戸内海シムレス河川・沿岸・海洋循環モデリング）

Summary

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論　文　の　要　旨

題　目　Unstructured Grid-based Seamless River-Coast-Ocean Circulation Modelling of the Seto Inland Sea
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As computational techniques advance, the scope of digital twins (DTs) is expanding to encompass entire cities, oceans, and even the Earth. Digital twins of oceans can provide highly comprehensive insights and predictions, thus enabling better-informed decision-making regarding ocean-related activities and management.

The Seto Inland Sea (SIS), located in western Japan, is the biggest semi-enclosed coastal sea with a length of approximately 450 km and an average depth of approximately 38 m. The population around the SIS is approximately 35 million in 2020 and it has a higher population density 1.9 times than the national average. Due to its unique shape, economic functions, and environmental management issues, the SIS has a great demand for interdisciplinary approaches.

The purpose of this study is to establish a robust, precise, and high-resolution model of the SIS that can be used as a base model for a digital twin of the SIS. In this early stage, we set an ocean circulation model using the Semi-implicit Cross-scale Hydroscience Integrated System Model (SCHISM) and validated circulations in the SIS.

The total numbers of nodes and cells were 210,505 and 390,461, respectively, covering the domain with lengths of 500 km × 420 km. The maximum resolution of the horizontal grid was approximately 30 m around Hiroshima Bay, one of the main study areas of the model. The spatial grid resolution of the model varied flexibly to describe all islands and straits in the SIS as long as the number of nodes and cells maintained a reasonable level in terms of the computation time. Thirty sigma levels were used for the vertical grid.

For the SCHISM model to simulate these areas without numerical errors, the spatially varying Shapiro filter was applied to this sea for the first time ever. It was critical for the numerical stability of the model even under diverse extreme conditions. Relatively higher filter parameter values were given at the nodes with high velocities and high resolutions near narrow straits with strong currents. Additionally, the available maximum value (0.5) was given at river areas where freshwater is discharged.

The modelling results were validated using observational datasets from forty-two tidal stations, one mooring system, thirteen water thermometers, and nine salinometers. It could depict barotropic components, such as tides and tidal currents, and a baroclinic component, such as water temperature and salinity, within the SIS. After the validation, it was applied to unusual cases, such as an abnormal tide in Hiroshima Bay and a storm surge in Osaka Bay by typhoons to secure the reliability of the model performance.

The abnormal tide is a non-periodic sea level variation, which can be caused by diverse meteorological or oceanic factors. The Itsukushima Shrine, one of the World Heritage Sites in Japan, is located in northern Hiroshima Bay in the Seto Inland Sea (SIS). The shrine was built on the seaside, 30 cm above the highest tide, to prevent it from submerging. However, the shrine was submerged five times during September from 2011 to 2022, due to the abnormal tides. The phenomenon was investigated in this study from the perspectives of Hiroshima Bay and the SIS scales.

Observed subtidal components of surface elevation in the northern part of Hiroshima Bay decreased due to

northerly winds when the typhoon passed east off the bay. After 7–8 days of typhoon passage, the component increased abnormally in the northern part of the bay. Simulation in the scale of Hiroshima Bay revealed that a destabilized density stratification by the typhoon winds most likely caused bay-scale internal waves. The internal wave propagated southward after the typhoon's passage and returned to the northern bay, causing the subtidal component to increase after 7–8 days. However, this process could reproduce only 15% of the observed abnormal tide, and it was impossible to explain the phenomenon fully within the limited scale of Hiroshima Bay.

The 2011 event was investigated by expanding the study area and implementing bias correction for sea surface heights (SSHs) at the open boundary. From the SIS model, we could reproduce not only the abnormal tide across the whole SIS but also other subtidal signals, implying the importance of signals developed within the SIS and propagated from the outside to the model performance. The prevailing circulation, the overall easterly throughflow due to the west high-east low SSH pattern in the SIS, was well reproduced as well.

Net fluxes of seawater crossing the Bungo Channel, the Kii Channel, the Kanmon Strait, and the Harima Nada were analyzed to investigate water sources inducing the sea level variations. Among the three connections, the Bungo Channel mainly determines overall net flux into the SIS and sea level variations in the SIS, while the Kii Channel has more important roles in circulation and local sea level variations.

The model with a coupling of the Wind Wave Model (WWM III) was applied to the extreme storm surge event by Typhoon Jebi in 2018. Typhoon Jebi in 2018 was the strongest tropical cyclone historically in the last 25 years. Typhoon Jebi induced a storm surge (sea level rise), especially in Osaka Bay. The maximum sea level height during the storm surge was calculated as 2.37 m. Two experiments were conducted to distinguish the main force causing surface currents. In the normal case, all forcings were considered, whereas tides were not considered in the sensitivity case. When Typhoon Jebi most closely approached Osaka Bay at 14:00 on 4 September 2018, ships anchored for safety got dragged due to unpredictable external forcings. The normal case demonstrated the additional strong currents at the surface layer, which was not noticeable from the sensitivity case without tides. It suggests that, when tidal currents and wind-induced currents aligned, enhanced currents tended to develop in the bay area, resulting in longer dragged distances of anchored ships, whereas only one forcing factor could not generate the currents.

A particle tracking model (OpenDrift) was applied to the SIS model result over 183 days (from 2 May to 1 November 2018) to analyze long-term pathways and fates of debris in the SIS by estimating trajectories of floating particles (passive tracers). The surface particles were divided into two groups along the Bisan-Seto Strait as a boundary, implying that the surface debris discharged into the western side of the SIS could not cross the Bisan-Seto Strait, therefore they kept staying on the western side for six months. When the northern winds by typhoons strongly acted on the SIS, the particles were transported outside the SIS through the Bungo Channel. This pattern was similar to the near-bottom particles. The particles staying on the western side were transported by anticlockwise and closed circulation inside after the Bungo Channel due to its bowl-shaped bathymetry. Only when strong winds by a typhoon modified velocity fields, the particles could be discharged outside the SIS through the Bungo Channel. Other particles which were deployed at the eastern SIS tended to be discharged outside of the SIS in a short period.

This study was focused on circulations in the SIS and explained how extreme events, usually typhoons, can affect the SIS, then showed reliable results so far. The results will help understand the physical process of the ocean further and establish evidence-based safety planning for natural hazard damage reduction. According to the terminology reviewed, the SIS model is currently categorized as a digital model since it simulates pre-existing ocean environments using past data without automatic data exchanges with the real world. However, it is imperative to undertake this fundamental step towards developing a digital twin of an ocean for the eventual realization of fully developed ocean digital twins. Additional modules, such as a sediment transport model, ecology/biology model, and water quality model, will be implemented in the future to produce and provide diverse information to various stakeholders. Then, a platform for the dissemination of this information will also be further developed.