Effects of wind waves on coastal currents: A case study of Typhoon Jebi, 2018

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INTRODUCTION

Typhoon Jebi in early September 2018 induced a storm surge around Osaka Bay. The typhoon had the strongest intensity among historical typhoons to come ashore in this area in the last 25 years (Le et al., 2019). It caused damaged coastal protection structures and a collision of a drifted tanker ship with a bridge (Kozono et al., 2019; Le et al., 2019). The damage of the hazard was investigated mainly using meteorological and wave models with a consideration of tide level to assess the impact of high waves on coastal infrastructure (Le et al., 2019; Otaki et al., 2022). The effects of tidal currents were not considered enough, although wind waves can be modulated by tidal modulation of water levels and currents. Also, the wave modulation, in turn, affects tidal components, called wave-tide interaction (Lewis et al., 2019).

The Seto Inland Sea (SIS) is a semi-enclosed coastal sea, including Osaka Bay. It has an area of approximately 23,000 km^2 and a length of 450 km, while Osaka Bay is 60 km in length. The whole SIS should be considered as study area if tidal effects must be analyzed accurately in Osaka Bay. This is because the SIS is an archipelago with narrow and complex straits, usually resulting in tidal asymmetry and tidal amplification or attenuation.

This study built an unstructured grid-based high-resolution hydrodynamic model of the SIS using the Semi-implicit Cross-scale Hydroscience Integrated System Model (SCHISM). The model was calculated using the Wind Wave Model III (WWM III) coupling to analyze the interaction between wind waves and tidal currents near coasts.

METHODOLOGY

The latest version (v5.9.0) of the SCHISM solves the Navier-Stokes equations in the hydrostatic form using the semi-implicit finite-element/-volume method, allowing stable simulations.

The WWM III can simulate the sea state from coastal areas to deep ocean on the same unstructured meshes with SCHISM by solving the wave action equation below,

$$\frac{\partial}{\partial t}N + \frac{\partial}{\partial x}(c_x N) + \frac{\partial}{\partial y}(c_y N) + \frac{\partial}{\partial \sigma}(c_\sigma N) + \frac{\partial}{\partial \theta}(c_\theta N) = S_{tot}$$

At the left side of the equation, each term indicates 'change in time', 'advection in spatial space', 'refraction due to depth', and 'refraction due to currents' of energy density, N. S_{tot} at the right side means the total source term. The number of wave directions was twenty-four, and wave frequency was divided into twenty-one frequencies ranging from 0.04 to 1.

Triangular mesh for the SCHISM was adopted to describe the complex coastal lines in the SIS. The maximum resolution of the mesh is approximately 30 m (100 m in Osaka Bay). The total number of nodes is 210,498, and the total number of cells is 390,712, with 30 vertical layers of sigma coordinates. Eight tidal components (M2, S2, K1, O1, N2, K2, O1, and P1) were inputted at the open boundary, and initial salinity, temperature, and current fields were also imposed. As meteorological forcings, 10 m winds (U10, V10), air pressure, air temperature, precipitation, downward radiation, and specific humidity were considered at the sea surface.

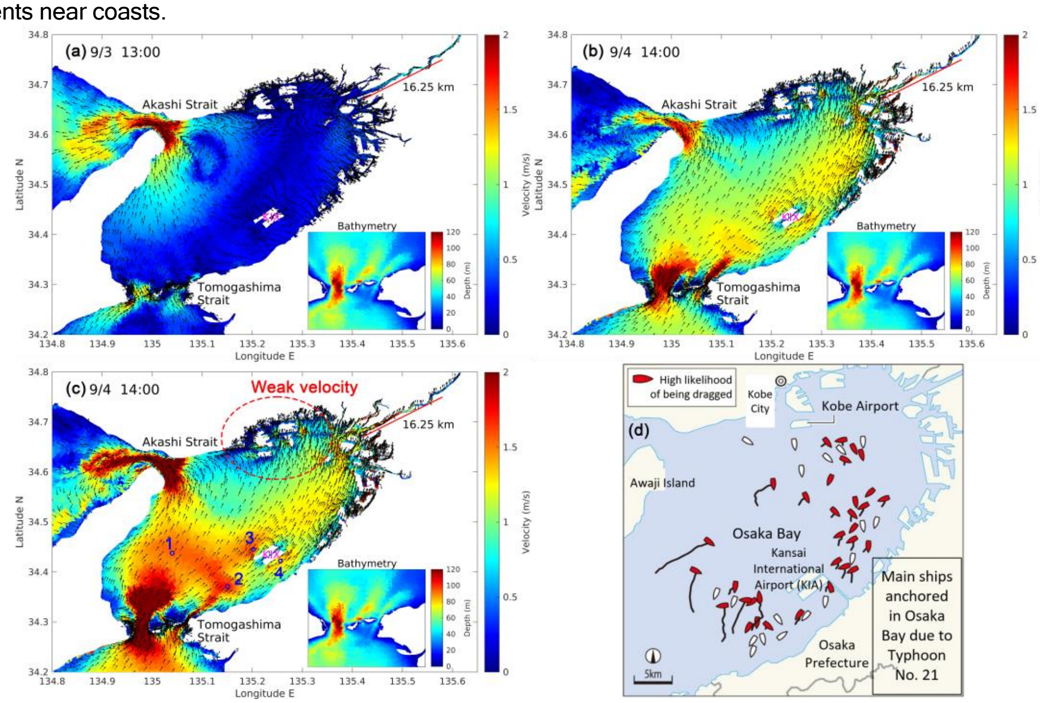

Figure 1 – Distributions of Surface currents from three cases: (a) Dominant tides with week winds, (b) only winds without tidal forcing, and (c) tides + typhoon winds. (d) Dragged distances of anchored ships by Typhoon Jebi (Wakabayashi et al., 2019).

RESULTS

The model results were validated and documented for elevations, currents, and temperature in Jeong and Lee (2023). The model reproduced reliable results similar to the observations. Salinity results at nine stations and wave results at 12 stations were validated and showed significant patterns during the typhoon season.

Two experiments were conducted to distinguish the main forcing causing surface currents in Osaka Bay. In the normal case, all forcings were considered, while in the sensitivity case, tides were not taken into account. The surface currents from three different conditions were compared in Figure 1. Figures 1a and 1c are the results from the normal case, while Figure 1b is from the case without tidal forcing.

When Typhoon Jebi most closely approached Osaka Bay at 14:00 on 9 September 2018, ships anchored for safety got dragged due to unpredictable external forcings, as recorded in Figure 1d. The model results also demonstrated additional strong currents at the surface layer at that moment (blue one to three in Figure 1c), which was not noticeable from Figure 1a-b.

The typhoon's arrival coincided with the flood tide as depicted in Figure 2. Therefore, when tides and winds were considered together, the surface velocity at the blue point 1 increased by 0.42 m/s (37%) from 1.13 m/s to 1.55 m/s compared to the only wind case. Also, 0.41 m/s (31%) and 0.22 m/s (16%) increased at point 2 and 3, respectively.

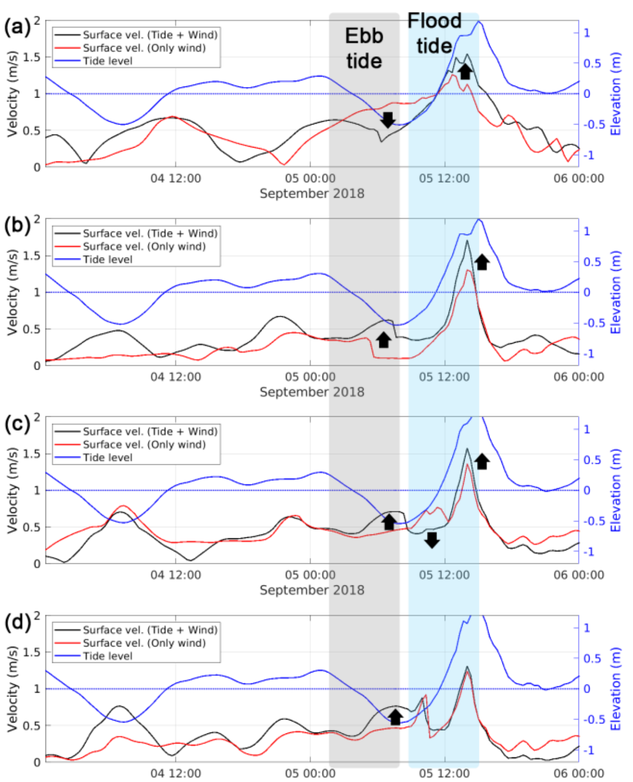

Figure 2 - Comparisons of the surface velocities between the normal case (black lines) and wind-only case (red lines) at points 1 to 4, respectively. Blue lines indicate surface elevations. The elevations exhibited peaks when Typhoon Jebi approached Osaka Bay.

It suggests that if only one forcing factor dominated, whether tides or surface winds, it generally induced currents only along the straits, as depicted in Figure 1a-b. However, when two forcings aligned, enhanced currents tended to develop in the bay area, resulting in longer dragged distances of anchored ships. Therefore, it is recommended that harbor management offices and ship navigators be aware of the possibility of abrupt currents and take proactive measures in advance.

The analysis so far has been focused on the areas deeper than 40 m. Interaction between tides and wind waves will be investigated further along the coastlines and artificial structures where the depth is shallower.

CONTRIBUTIONS

This study aims to understand the reason for severe damage from Typhoon Jebi from the perspective of interactions among tides, wind-driven currents, and waves. The model of this study describes complex coastlines in Osaka Bay due to artificial structures. This study will allow us to investigate how tidal components interact with waves behind the artificial islands and how much storm surge and waves propagate and run up along river mouths.

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