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Abnormal High Tides and Flood Induced by Internal Surge in Hiroshima Bay due to a Remote Typhoon

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Itsukushima Shrine, located in the northern part of the semi-closed Hiroshima Bay, is a beautiful and high cultural-valued structure preserved as one of the World Heritage sites in Japan. The shrine was built offshore, 30 cm above the highest tide to prevent it being submerged. However, from 1991 to 2012, the shrine has been submerged 6 times at high tides mostly in September due to abnormal high tides in the bay. In September 29 in 2011, an abnormal high tide occurred in the northern Hiroshima Bay and caused a flooding of the shrine. A case study for the 2011 flood event based on an acoustic tomography survey revealed that the northern bay flood was caused by an internal surge which was induced by northerly winds due to a remote typhoon passing through the eastern part of the Seto Inland Sea approximately 400 km east of Hiroshima Bay. Thus, in this study, an unstructured grid circulation model for Hiroshima Bay was established and applied to verify the precise mechanism of the internal surge and consequential abnormal tide.

Semi-implicit Cross-scale Hydroscience Integrated System Model (SCHISM) with a semi-implicit time stepping for numerical stability was used for the circulation modelling in the bay. Ota River, the source of freshwater, has narrow tributaries, thus it demands a high-resolution and stable model for its description with flexible grid system (Fig. 1). To simulate the surge that occurred on September 29 in 2011, boundary conditions for tide, river discharge, and atmospheric flux in the bay are considered from tidal harmonic constants from finite element solution (FES) tide model, river discharges from the Ministry of Land, Infrastructure, Transport and Tourism, and surface winds and pressure from the meso scale model (MSM) by the Japan Meteorological Agency (JMA) as atmospheric fields, respectively. The four-dimensional variational ocean re-analysis for the Western North Pacific over 30 years (FORA-WNP30) by Japan agency for marine-earth science and technology (JAMSTEC) was utilized for an initial and boundary conditions for temperature and salinity profiles.

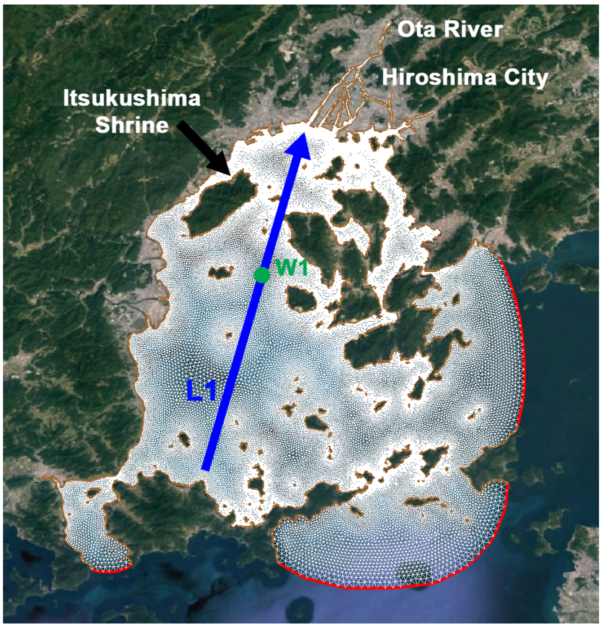

Figure 1. A map of Hiroshima Bay and computational meshes generated for SCHISM.

The northerly winds by a remote passing typhoon exited the well-stratified bay water in September 2011. In the upper mixed fresh layer overlaying the more saline layer in the stratified seawater of the bay, southward surface currents were generated, and the warm surface water was transported and filed up in the southern part of the semi-closed bay (Fig. 2c-d).

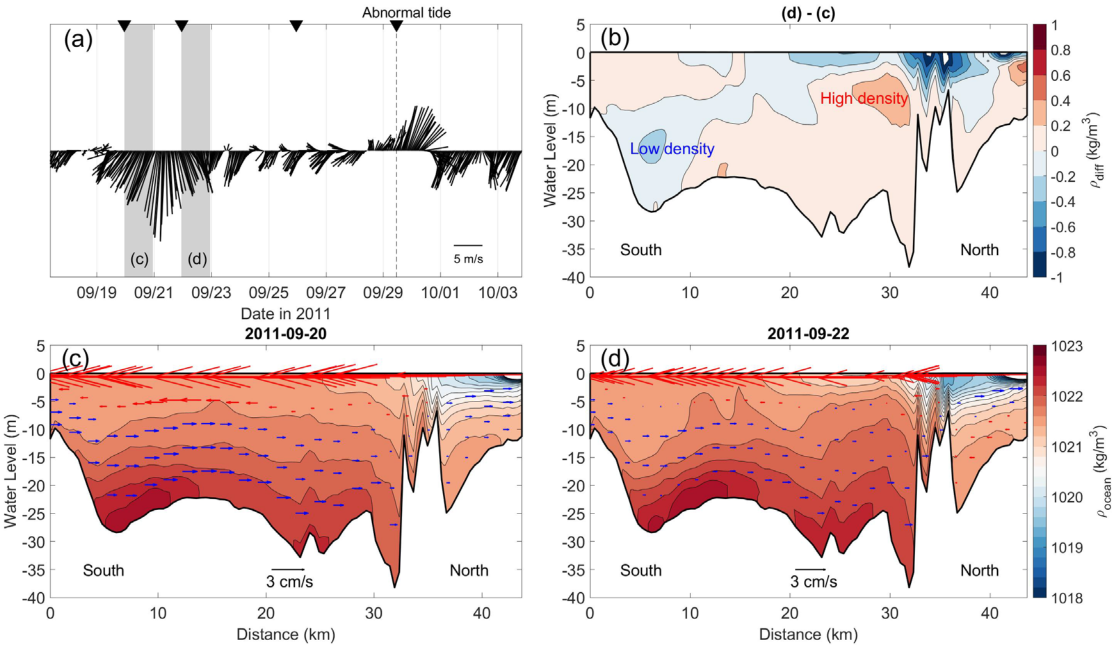

Figure 2. (a) Wind vectors at W1 from meso scale model (MSM) of Japan Meteorological Agency (JMA). (c)-(d) Transects for the daily mean density profile and circulation from the model result along L1. Vectors are indicating currents toward south (north) as red (blue) vectors. (b) A transect for the density difference between (c) and (d).

It caused a horizontal gradient between the northern (higher water level) and the southern (lower water level) parts of the bay (Fig. 3b) and between the enhanced southern (thicker) and the reduced northern (thinner) mixed layers (Fig. 2d). Even after the northerly winds disappeared, the southward currents and wind set-up drew the relatively cool and saltier lower layer water northward, which caused the internal surge due to upwelling in the northern bay (Fig. 3d). Then, if the internal surge and upwelling occur at high tide, it causes the abnormal high tide and flood as in September 29 in 2011. The constructed unstructured grid circulation model for the Hiroshima Bay simulated the 2011 September event well and revealed those physical mechanism of the surge and upwelling in the bay. The results can be universally applied to a semi-closed bay or closed water body for internal wave generations and propagation under specific meteorological conditions and used for safety and disaster management for not only shrines, but also coastal structures close to the shoreline.

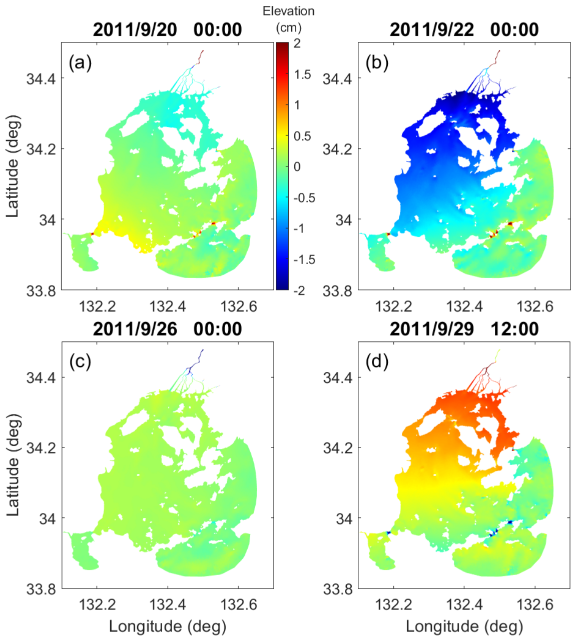

Figure 3. Band pass [4 – 15 days] filtered elevation distributions from the model results. Distributions were taken (a) just before the typhoon, (b) just after the typhoon, (c) 2 days after the typhoon passed, and (d) when the abnormal tide occurred. Wind vectors at each time can be informed with downward-pointing triangles in Fig. 2a.