Salinization by a tsunami in a semi-enclosed bay: tsunami-ocean three-dimensional simulation based on a great earthquake scenario along the Nankai Trough

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Abstract. This study investigated the influences of a giant tsunami on salinity in coastal waters based on the scenario of the largest potential tsunamigenic earthquake that could occur along the Nankai Trough in the near future, by conducting an ocean-tsunami coupled three-dimensional simulation in Osaka Bay. This realistic simulation using an unstructured-grid model was capable of evaluating the oceanic salinization induced by the tsunami. Simulated results indicated that tsunami intrusion into the bay head increased salinity and it returned to its previous value within 1 week after the earthquake. The salinization, which continues for a few days, may adversely affect the local brackish biota.

Keywords: Tsunamigenic earthquake along the Nankai Trough, Giant tsunami, Salinization, Brackish biota, Ocean-tsunami coupled three-dimensional simulation, Finite-Volume Community Ocean Model

1. Introduction

A giant tsunami generated by a strong earthquake can dramatically change physical structures and environments (e.g., temperature, salinity, and density) in the semi-enclosed coastal ocean. For example, Ref. [1] reported that the tsunami caused by the Tohoku Region Pacific Coast Earthquake on March 11, 2011 transported saline water into a semi-enclosed inlet, leading to an increase in salinity and density of marine phytoplankton in the inlet both vertically and horizontally after the tsunami. Thus, as a result of tsunami intrusion, dramatic changes in salinity can strongly influence coastal ecosystems, including causing massive blooming of
oceanic plankton and potentially serious red-tide formation.

Figure 1: Integrated system for ocean-tsunami simulation using domains (a) in the ocean prediction system with salinity and stream fields (color and arrows) and (b–c) in the tsunami model with bathymetry and rapture model. (d–f) Domain resolved by unstructured-grid for the Finite-Volume Community Ocean Model (FVCOM) in our study area (red squares). Blue lines and arrows show the data stream from the ocean and tsunami prediction for open boundary conditions.
The Japanese government has reported that a strong Nankai Trough Earthquake will occur with approximately 70% probability within 30 years and will cause a giant tsunami [2]. However, to our knowledge, no assessments of ocean salinization in the waters of this coast have been performed by simulating salinity fields influenced by the intrusion of a tsunami. This study evaluates the salinization induced by the giant tsunami that would be expected to intrude into the semi-enclosed bay, based on the anticipated strong earthquake scenario along the Nankai Trough. Our study area is the Osaka Bay (Fig. 1), which possesses numerous landfills in the nearshore area, as a pilot ocean to evaluate salinization.

2. Integrated system for tsunami-ocean coupled simulation

We integrated the ocean prediction system, DREAMS [3,4] and tsunami prediction model [5, 6] into a single ocean-tsunami simulation system using the nesting method (Fig. 1a–c). For the ocean-tsunami simulation, a prognostic, unstructured-grid Finite-Volume Community Ocean Model (FVCOM version 3.1.6) was utilized (Fig. 1d–f), which was originally developed by Ref. [7] as a coastal ocean general circulation model. The unstructured triangular grid with a terrain-following, σ-z mixed coordinate in the vertical, provides flexibility in adjusting the grid resolution and better fitting of irregular coastal geometries and bathymetry. The finite-volume approach ensures the conservation of mass, heat, and salt, so that it is capable of reproducing the key physical processes. We synthesized the open boundary conditions given in the FVCOM from the tsunami simulation results (tsunami wave height and velocity) and ocean prediction system that provided the water level, temperature, salinity, and velocity of ocean currents, including the tidal signals (Fig. 1).

We focused on the tsunami occurring in summer to consider the condition of a dominant halocline to facilitate the evaluation of salinization in the bay. The initial conditions of water temperature and salinity used in the ocean-tsunami simulation were produced by inner-extrapolation using a Gaussian function, based on the long-term averages of the observational data for July obtained from the Marine Information Research Center (MIRC), Japan Hydrographic Association for the period from 1963 through 1994. The ocean-tsunami simulations were started from an initial state of rest for more than one month from July 1, 2014 based on the tsunamigenic earthquake scenario along the Nankai Trough, by assuming seafloor changes (Figure 1b) estimated by a seismic rapture model (Case 3) that most severely affect the bay among 11 cases [8]. The simulated results for 1 week show the typical features of the ocean environment often observed in Osaka Bay; e.g., the river plume from the Yodo River, summertime thermocline, etc. We assumed that the earthquake occurred in summer, on July 20, 2014. The halocline is often observed in the coastal ocean with low-salinity water in the surface layer. We employed the merged bathymetry dataset for regional tsunami models.
used in Ref. [9] and assumed that the tsunami reflects off the coastal line and does not run up onto the land for the sake of simplicity. Reanalysis and predicted meteorological GPV–MSM (Grid Point Value datasets of the Meso-Scale Model) datasets were input into the FVCOM using the mean hourly air temperature, precipitation, cloud cover, relative humidity, dew-point temperature, and wind speed. Climatological river discharges used in the simulation were given by the estimated runoff data based on the water level data observed upstream of the estuaries of the Yodo and Yamato Rivers, and other small rivers. The river discharge data in 2014 have been not submitted from related agencies to the public database yet.

Figure 2: Snapshots of (upper panels) surface sea salinity distribution and velocity fields in the bay head, and (lower panels) salinity changes caused by a tsunami at 03:00 JTC, July 20, and midnight, July 21 and 28. The salinity changes were calculated from the difference between the salinity simulation with and without the tsunami (Case CR minus Case NR).
The numerical simulations of tsunami intrusion into the bay (Case CR) were conducted for a period of 8 days following occurrence of the earthquake. Additional simulation without the tsunami was conducted, referred to as Case NR. By analyzing the difference between the results of Cases CR and NR (CR minus NR), we can evaluate the influence of the tsunami on salinity in the bay.

3. Results and Discussion

The FVCOM-simulation was capable of reproducing the giant tsunami for the height and phase speed of the tsunami similar to previous reports. As an example, Figure 2 shows three snapshots of the surface sea salinity distribution and its changes. The salinity changes were calculated by the difference of Case CR minus Case NR. The left-upper panel in Figure 2 shows the salinity and velocity field after the initial leading tsunami wave had reached the northeastern coast. A second tsunami wave propagating toward the coast was observed around the bay head. Whereas the salinity around the bay head was low (<20) under the influence of the large volume of Yodo River runoff, the salinity increase induced by the tsunami was visible in its estuary. One day after the earthquake (middle panels), a salinity increase of >5‰ (up to 10‰) was induced in the bay head by the intrusion of the tsunami into the bay and mixing in the shallow water. Thus, the coastal water was significantly salinized in the bay head. Eight days after the earthquake (right panels), the salinization had been completely reversed (salinity <20) by seawater exchange due to the diffusion and advection attributed to tidal and wind-driven currents, although a local salinity increase remained in nearshore water.

Figure 3 shows the time series of the area-averaged tsunami wave height and salinity change across the shallow bay head (depth <~20 m). The upper panel shows that a sharp increase in the area-average salinity occurred after the leading or first tsunami wave reached the coast. A maximum increase in salinity of ~4‰ occurred from the period when the second wave reached the coast, and reached a local maximum of ~10 1 day after the earthquake (not shown). The salinization gradually decreased due to water exchange with the decay of the subsequent oscillation of the tsunami wave within 1 week after the tsunamigenic earthquake (lower panel).

Figure 4 shows the temporal variation of the salinity change in nearshore waters around three cities, Nankou, Fukae, and Amagasaki (Figure 1). A large salinity increase remained in Fukae and Nankou on July 22 (Day 3 after the earthquake). Severe salinization (ΔS >3‰) continued in these areas, although the salinity continued to increase at Fukae until July 24 due to the small volume of water exchange at this location, facing the semi-enclosed water around the landfills. However, a large fluctuation in the salinity changes at Nankou was visible, which was mainly induced by the tidal and wind-driven currents. The salinity change of ΔS
~2% at Amagasaki near the Yodo River estuary gradually decreased to 0 on 24 July (Day 5 after the earthquake). Thus, salinization of the region in the semi-enclosed water around the landfills may continue for approximately 5 days after the earthquake.

Figure 3: Time series of the area-averaged tsunami wave height (red lines) and salinity change (black lines) across the shallow bay head in the western area from 135.2°E (upper panel) 1 day and (lower panel) 8 days after the earthquake.

Figure 4: Temporal variations of the salinity changes induced by the tsunami in nearshore waters around three cities (Fig. 1): Nankou (blue), Fukae (red), and Amagasaki (green), during the period from 3 to 8 days after the earthquake.
The region in the semi-enclosed bay head contains brackish water and supports a corresponding ecosystem. The local salinity changes induced by the giant tsunami may influence the brackish biota (e.g., bivalves and flatfishes) occurring in the nearshore water of the bay head; e.g., the adults of *Corbicula japonica* Prime, one of the important fishery bivalves in the bay. Figure 5 shows that their number decreased by approximately 50% 4 days in the high salinity water (32‰) and was 0 on Day 6 at 25°C, corresponding to a representative water temperature for July [10]. The number of juveniles decreased to approximately 40% and 0 in high-salinity water of 28.5‰ and 32‰, respectively, until Day 6 in summertime water temperature (20°C). In the case of the region around Fukae, a salinity increase of 3‰ from 29‰ due to the tsunami, over a period of 5 days, can adversely affect the habitat of bivalves. A similar scenario applies to the case of the juveniles of flatfishes, for example *Kareius bicoloratus*. This is because they have insufficient swimming capability to escape from the extensive area of high salinity water induced by the tsunami, and <60% of their number can survive in high-salinity water (>33.4‰), compared with approximately 90% in low-salinity water (<25‰) [11].

![Figure 5: Effects of high salinity on the survival of adult and juvenile *C. japonica* at 30°C (after Nakamura et al., 1996).](image)

4. Summary

This study demonstrated that an ocean-tsunami coupled model generated by combining a real-time ocean prediction model and unstructured-grid FVCOM is capable of simulating the salinization induced by the giant tsunami predicted to enter a semi-enclosed bay. We provided an evaluation of the oceanic salinization based on the ocean-tsunami simulation using the seafloor change anticipated by a seismic fault model along the Nankai Trough as the initial condition to generate the tsunami. The two main findings based on our simulated results can be summarized as follows: 1) a salinity increase (average of ~4‰) in the bay head induced by the tsunami intrusion and mixing during the period when the leading tsunami wave and se-
cond wave reaches the coast; and 2) a reversal of the induced salinization by seawater exchange via the diffusion and advection of tidal and wind-driven currents within 1 week after the earthquake. The high-salinity water induced by the giant tsunami may damage the local brackish biota (e.g., bivalves, flatfishes) in the semi-enclosed water regions when it continues for a period of a few days. Mitigation measures for tsunami hazards in the ocean environment should be based on accurate and realistic tsunami simulations, including oceanic variations.

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