Characteristics of transoceanic tsunamis: observation and modeling

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Background

A transoceanic tsunami is a tsunami that travels across an entire ocean basin, originating from a distant source—typically more than 1,000 km away or requiring over three hours of travel time to reach the affected coast. These events are usually triggered by very large earthquakes and can impact countries far from the epicenter. Satake et al. (2020) studied various instrumentally recorded transoceanic tsunamis, including the 1854 Nankai earthquakes (Japan), the 1946 Aleutian earthquake tsunami (USA), the 1960 and 2010 Chile tsunamis, the 2004 Indian Ocean tsunami (Indonesia), and the 2011 Tohoku tsunami (Japan). Transoceanic tsunamis have been a major concern for the safety of coastal communities and assets, particularly because even though they are generated at a substantial distance, they can still cause devastating impacts. However, the scarcity of modern observational data on transoceanic tsunamis makes it difficult to comprehensively quantify their characteristics.

Keyword: Transoceanic tsunami, numerical simulation, spectral and wavelet analyses, coastal morphology responses.

Objectives

The July 2025 Mw 8.8 Kamchatka tsunami offers a rare opportunity to advance understanding of transoceanic tsunami propagation using high-quality data from 40 DART stations and 10 tide gauges across the Pacific (Fig. 1). Using those data, this study aims to achieve three main objectives:

- Validate existing finite-fault earthquake source models to simulate tsunami generation and propagation across the Pacific Ocean.
- Compare simulations with high-quality observational data from DART stations and tide gauges to capture far-field propagation dynamics.
- Quantify the influence of earthquake source parameters (rupture directivity, strike, length, slip), including coastal morphology responses on tsunami behavior through statistical, spectral, and wavelet analyses.

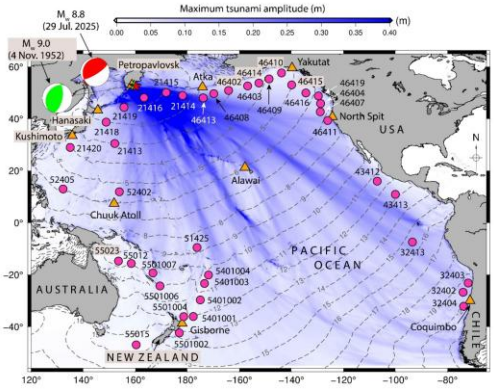


Figure 1. Location map of the Pacific Ocean showing the epicenter of the 29th July 2025 Mw 8.8 Kamchatka earthquake (red star), that of the 1952 earthquake (green star), respective focal mechanisms, DART stations (pink circles), tide gauges (orange triangles).

Methods

Earthquake and Tsunami Source Models

We use the United States Geological Survey (USGS) latest three source models (https://earthquake.usgs.gov/earthquakes/eventpage/us6000qw60/executive, accessed 23/01/2026) for our tsunami simulations. The USGS finite fault slip models are jointly determined by teleseismic P and SH waves and long-period surface waves.

Tsunami Propagation Modelling

Tsunami propagation will be simulated using the JAGURS tsunami package (Baba et al., 2015, 2020). The model solves the long-wave or shallow-water equations on a spherical coordinate bathymetric grid using a staggered, leap-frog finite-difference scheme.

Phase Correction Method

The inherent transoceanic travel-time delays associated with the long-wave tsunami simulation are also evident in our study. This is attributed to various geophysical factors, such as seawater compressibility, the Earth's elasticity, and geopotential perturbations. To incorporate these effects into our simulated tsunami waveforms, we implement the phase-correction method proposed by Watada et al. (2014).

Spectral and Wavelet Analyses

After removing the tidal signal, DART recordings will be resampled to a uniform 15 s interval to facilitate the spectral and wavelet analyses. In addition to waveform comparison, we will investigate the frequency-energy characteristics of tsunami signals using power spectral density analysis based on an updated version of the Welch (1967) method with half-overlap windows.

Results

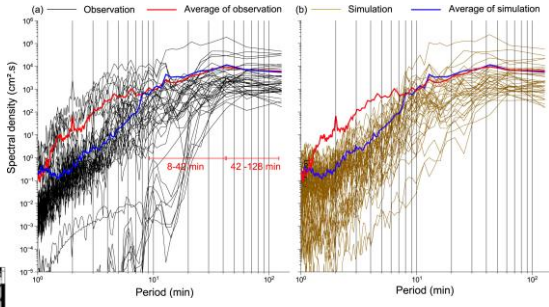


Figure 2. Spectral analysis for the tsunami generated by the 29 July 2025 Mw 8.8 Kamchatka earthquake. (a) The black thinner lines represent observed spectra of the DART waveforms shown in Fig. 5. (b) The brown thinner lines represent corresponding simulated spectra.

Averaging the spectral results across all DART stations confirms the 8–128 min tsunami energy band (Fig. 2), which can be distinctly divided into two period bands: 8–42 min and 42–128 min. Generally, the simulations agree with observations, particularly at longer periods. The 45-arcsec (~1.3 km) grid is sufficient to resolve approximately 8 min tsunami wave periods in the deep ocean, while shorter-period waves, such as approximately 3 min, approach the resolution limit and may be under-resolved (Baba et al., 2020).

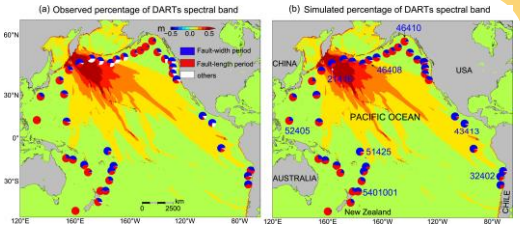


Figure 3. Geographical distribution of the contributions of different source effects to the total tsunami spectral energy, shown using pie charts for the tsunami generated by the 29 July 2025 Mw 8.8 Kamchatka earthquake. (a) Observations. (b) Simulations.

Fig. 3 shows that, for stations aligned with the fault strike direction, the 42–128 min period band dominates the total energy, accounting for more than 50% of the total spectral energy at most stations. Conversely, for stations aligned in a direction normal to the fault strike, the 8–42 min period band dominates the total energy, with the energy contribution approximately 50% at most of stations as well.

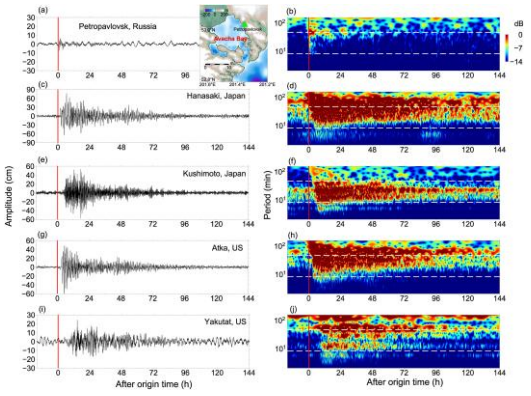


Figure 4. Wavelet analysis for tsunami waveforms from the July 2025 Kamchatka tsunami recorded at five tide gauges across the Pacific Ocean.

Fig. 4a and b shows that waveforms and wavelet plots for tide gauge station at Petropavlovsk (Avacha Bay, Kamchatka peninsula), the nearest station to the source zone, only 110 km away from the epicenter. It exhibits the minimum wave among the other tide gauge stations with maximum amplitude of only 5.0 cm, the lowest wavelet energy intensity, and the shortest wavelet oscillation duration. In contrast, tsunami signals recorded at the remaining nine Pacific Ocean stations were marked by substantially higher wave amplitudes and prolonged wavelet energy oscillations.

Conclusions

- Directional control by source geometry: transoceanic tsunami amplitudes and spectral energy distributions are strongly dependent on the orientation relative to the fault.
- Integrated source–propagation–coast analysis: By linking seismic source characteristics with deep-ocean and coastal observations, we reveal the systematic partitioning of spectral energy across the Pacific Ocean.
- Complex coastal impacts of broad source band: The broad nature of the Kamchatka 2025 source spectra produces enhanced coastal responses across the Pacific.