



Basin-Scale Geometric Focusing: A Probabilistic-Geometric Framework for Global Tsunami Hazard Assessment and the 2025 Kamchatka Peninsula Tsunami

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Abstract. We present a hybrid probabilistic-geometric framework that integrates probabilistic earthquake statistics with large-scale ray-tracing simulations to efficiently map global coastal tsunami exposure. Utilizing a catalog of historical tsunami-genic events and the Gutenberg-Richter relation, we derive probabilistic weights for over 9,000 rays released across potential fault zones. The simulated ray pathways reveal persisting bathymetry-driven energy convergence patterns that govern far-field coastal focusing and shadowing. The geometric framework's predictive power is demonstrated using the 2025 M8.8 Kamchatka Peninsula event. Validation against the 2025 M8.8 Kamchatka earthquake utilizes phase-corrected FUNWAVE-TVD simulations and in-situ DART observations. The resulting ray-based coastal focusing patterns display a substantial qualitative and quantitative spatial agreement (Spearman's $\rho = 0.66$) with the transoceanic maximum wave amplitudes from the high-fidelity FUNWAVE-TVD model. This agreement confirms the hybrid probabilistic-geometric approach as a scalable and computationally efficient tool for rapidly identifying coastal hotspots of transoceanic tsunami impact.

1 Introduction

Transoceanic tsunamis, typically generated by large-magnitude megathrust earthquakes in subduction zones, represent one of the most far-reaching and destructive natural hazards to coastal populations worldwide. As these long-wavelength waves traverse entire ocean basins, their energy does not disperse uniformly. Instead, the complex three-dimensional structure of ocean bathymetry, comprising mid-ocean ridges, fracture zones, seamount chains, continental shelves, and deep-ocean trenches, acts as an intricate system of refractive lenses. This bathymetry-driven refraction can channel, redirect, and sometimes trap tsunami rays, producing regions of pronounced geometric focusing. The resulting distribution of tsunami energy at landfall is highly heterogeneous: some coastlines, even thousands of kilometers from the source, experience severe and often unexpected wave amplification, while other areas may remain largely unaffected, forming classical shadow zones. This basin-scale sensitivity to



20 bathymetric structure highlights the need for reliable tools capable of resolving the principal ray pathways that govern far-field tsunami exposure, especially given that these spatially variable pathways originate from the heterogeneous source distribution shown in Figure 1a.

While tsunamis can be triggered by non-seismic sources such as submarine landslides or volcanic eruptions, the vast majority of basin-wide events are generated by submarine earthquakes, which account for approximately 80% of all recorded damaging tsunamis (Davies et al., 2018; Behrens et al., 2021). Non-seismic tsunamis, although potentially devastating in the near field, typically involve more localized sources that produce shorter-wavelength waves. These waves are more susceptible to frequency dispersion, causing their energy to decay more rapidly with distance and limiting their far-field significance (Løvholt et al., 2008; Torsvik et al., 2021). For this reason, the present study focuses exclusively on the far-field propagation of seismically generated tsunamis. Accordingly, the framework is not intended to replace detailed near-field inundation or run-up modeling, but to identify which distant coastlines merit such analysis. We explicitly exclude the complex, nonlinear, and site-specific nearshore processes of shoaling, breaking, inundation, and run-up, which constitute a separate modeling domain. This far-field focus is critical because the identification of transoceanic energy corridors serves as a necessary first step for prioritizing resources and allocating computationally intensive nearshore modeling (run-up and inundation) to the most vulnerable coastal communities.

30 Given the strong influence of bathymetric refraction on transoceanic tsunami propagation, there are fundamentally two approaches for examining these basin-scale convergence patterns. The first is to employ numerical models, which resolve the detailed physics of tsunami generation and evolution, but become computationally prohibitive when applied to global domains or to the large scenario ensembles required for hazard analysis. The second option is to utilize more cost-effective geometrical-optics methods, so-called ray tracing, which captures the dominant effects of bathymetric refraction at a fraction of the computational cost. In one of the earliest demonstrations of this concept, Satake (1988) adapted seismic ray-tracing techniques to tsunami propagation, showing that tsunami rays can accurately reconstruct the principal propagation pathways and identify the bathymetric features responsible for focusing and defocusing. These foundational results established ray tracing as a powerful and efficient tool for exploratory analysis, scenario screening, and rapid basin-scale hazard evaluation.

A recent study by Tehranirad et al. (2015) further reinforces the utility of ray tracing as a robust proxy for tsunami energy assessment. Focusing on a large-scale volcanic flank collapse at Cumbre Vieja Volcano (La Palma) in the Atlantic, they compared ray-tracing predictions with high-resolution Boussinesq simulations using FUNWAVE-TVD and found a strong spatial correlation between ray convergence patterns and maximum surface elevations. This effectively benchmarked the geometric-optics approach against a fully nonlinear dispersive model, demonstrating that continental-shelf ray concentration reliably identifies zones of elevated tsunami impact. Importantly, that study dealt with a landslide-generated tsunami, where shorter wavelengths and significantly higher kd values, where k is the wavenumber and d is the undisturbed water depth, produce stronger dispersion conditions typically cited as limitations for ray-based methods. Yet the agreement remained high, implying that for seismically generated tsunamis, which are ideal for the geometric optics approach because they are dominated by the non-dispersive shallow-water approximation, where the wave celerity $C_p = \omega/k = \sqrt{gd}$ does not depend on wave length, and exhibit lower dispersion over transoceanic distances, ray tracing should be even more accurate. Thus, the validation by



Tehranirad et al. (2015) directly addresses one of the central criticisms of ray theory and strengthens its relevance for global-scale seismic tsunami hazard assessment, including the Kamchatka case analyzed herein.

However, identifying the pathways of geometric focusing represents only one component of the broader hazard assessment problem. A realistic global hazard assessment must also reflect the inhomogeneous recurrence rates of tsunamigenic earthquakes across subduction systems. Early ray-based studies were inherently deterministic, typically initiated from a single, hypothetical earthquake source. Such simplified treatments do not capture the full range of seismic variability across global subduction systems and therefore cannot produce a comprehensive or realistic depiction of global tsunami hazard. Modern hazard assessments must confront two key challenges: (1) the probabilistic nature of earthquake occurrence across distributed and heterogeneous source zones, and (2) the computational scalability required to evaluate tens of thousands of plausible rupture scenarios. This latter requirement motivates the use of Probabilistic Tsunami Hazard Assessment (PTHA), a framework that quantifies risk by estimating the exceedance probabilities (or return periods) of tsunami intensities at specific locations. PTHA couples statistical models of earthquake recurrence, often based on the Gutenberg-Richter relation, with numerical or analytical models of tsunami generation and propagation. Comprehensive reviews such as Grezio et al. (2017) outline how PTHA can be applied at regional to global scales by integrating multiple source zones to construct hazard curves and probability maps.

To address this methodological gap, we introduce a hybrid probabilistic geometric modeling framework that couples classical ray tracing with earthquake probability statistics to produce a fast, scalable, and scientifically robust global hazard mapping tool. Our approach integrates Gutenberg-Richter-based frequency-magnitude relationships with large-ensemble ray tracing simulations, enabling efficient evaluation of far-field tsunami exposure while retaining the essential bathymetric controls. In our implementation, more than 9,000 rays are released from candidate fault segments worldwide, each ray assigned a probabilistic weight derived from local and regional seismicity rates. This approach allows us to rapidly quantify coastal energy convergence and identify global tsunami hotspots most susceptible to long-range focusing, while providing a probabilistic interpretation of exposure consistent with modern hazard assessment standards.

This paper is organized as follows. Section 2 presents the Probabilistic Tsunami Hazard Assessment (PTHA) methodology. Historical seismological data are analyzed to map the spatial distribution of tsunamigenic sources and to estimate their return periods for earthquakes exceeding magnitude 7.4. Section 3 introduces the wave ray tracing method, based on the principles of geometrical optics. This approach simulates tsunami propagation paths from the PTHA-identified source regions, with the resulting ray patterns revealing how ocean basin geometry and bathymetric refraction generate zones of energy focusing and shadowing. These patterns provide a first-order assessment of regional tsunami hazard. Section 4 presents a validation case study of the M8.8 Kamchatka Peninsula earthquake. It begins with a high-fidelity Boussinesq-type simulation using the FUNWAVE-TVD model, hereafter referred to as FUNWAVE, to compute tsunami wave amplitudes. Next, the ray-tracing model is applied to predict tsunami energy convergence zones (focal points) for the same event. The resulting numerical simulations are compared against in-situ observations to assess both the accuracy of the ray-tracing predictions of focal zones and the wave heights simulated by FUNWAVE. Finally, Section 5 summarizes the findings and provides concluding remarks.

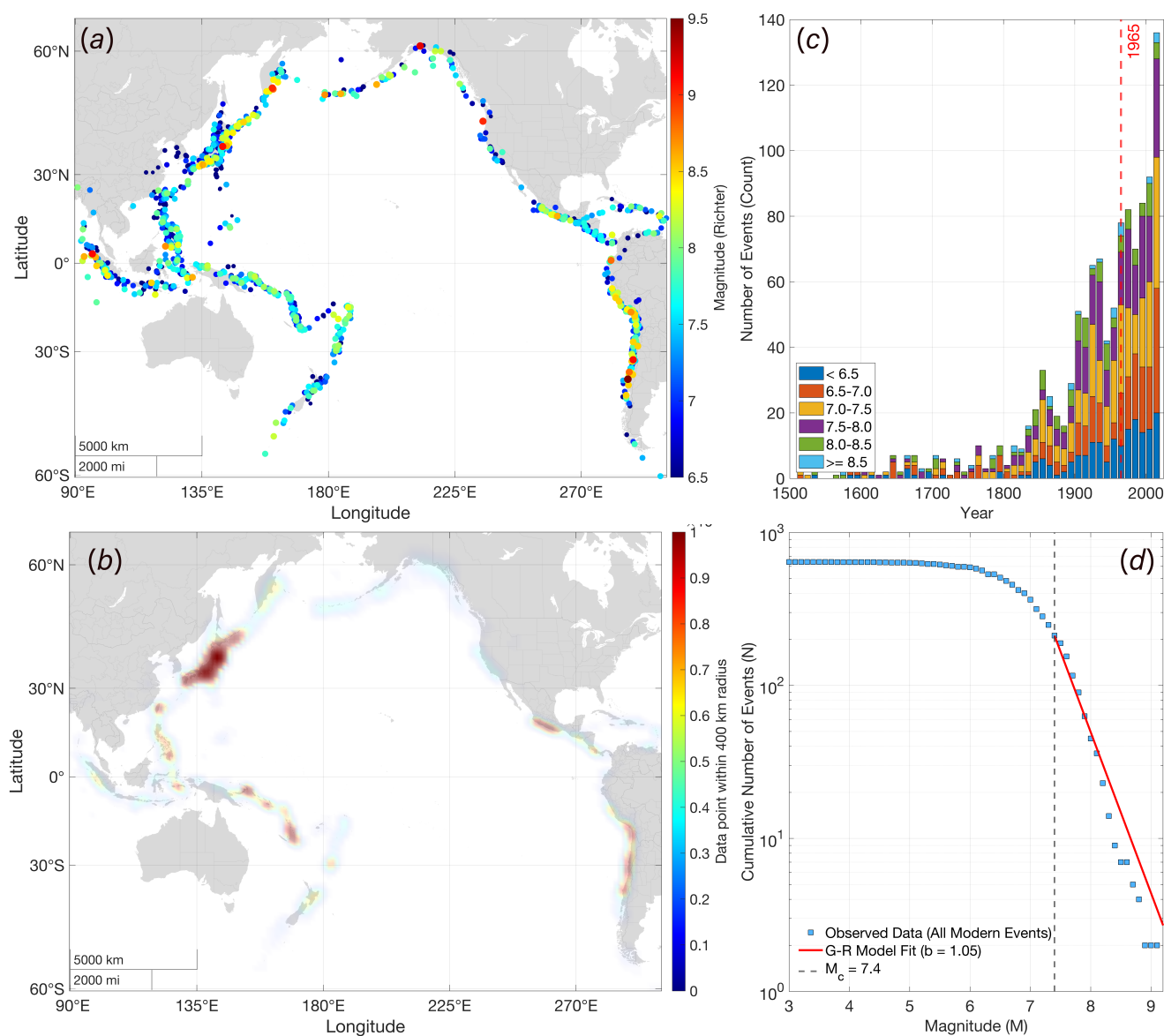


Figure 1. (a) Historical tsunamigenic earthquakes based on ~1600 events from ~500 BCE to 2025. The colormap indicates event magnitude on the Richter scale; (b) Spatial density plot (heatmap) showing earthquake clustering, calculated with a 400 km radius of influence; (c) Histogram of historical events per decade since 1500, with bars color-coded by event magnitude. The vertical red line at 1965 marks the start of modern event records used in this study; (d) b-value estimate, showing the Gutenberg–Richter model fit (red line) to historical data since 1965 for events of magnitude ≥ 7.4 . Basemap created with Natural Earth data.



2 Probabilistic Tsunami Hazard Assessment

To create a spatially variable weighting scheme for tsunami sources, a simplified Probabilistic Tsunami Hazard Assessment (PTHA) was conducted (Grezio et al., 2017). The process is based on deriving earthquake recurrence parameters from a historical catalog NGDC/WDS (2024) of tsunamigenic events and applying these parameters to a set of discrete source points along known and potential earthquake zones. The final output is the mean annual rate of occurrence for earthquakes, which serves as a quantitative weight for the subsequent ray tracing model.

The historical catalog comprises approximately 1,600 global events. Figure 1a illustrates the spatial distribution of these events, where color indicates the magnitude of tsunamigenic earthquakes recorded from 500 BC to 2025. Panel b shows the occurrence rate, while panel c presents the decadal histogram color-coded by magnitude. The establishment of the World-Wide Standardized Seismograph Network (WWSSN) in 1965 is marked by a vertical red line.

2.1 Gutenberg–Richter Recurrence Relationship

The frequency-magnitude distribution of earthquakes is modeled by the Gutenberg–Richter (G-R) law:

$$\log_{10}(N) = a - bM \quad (1)$$

where N is the cumulative number of earthquakes with a magnitude greater than or equal to M . The parameter b describes the relative proportion of small to large earthquakes, while the a -value represents the overall seismic productivity of a region.

To determine a stable b -value, the catalog was filtered to include only the modern instrumental period (1965 onward), corresponding to the establishment of the World-Wide Standardized Seismograph Network (WWSSN). A Magnitude of Completeness (M_c) of 7.4 was determined by visual inspection of the frequency-magnitude distribution (consistent with completeness levels found in global subduction-zone catalogs). Based on the resulting subset of 212 events, a b -value of 1.05 was calculated using the Aki–Utsu maximum likelihood estimator (Figure 1d) (Aki, 1965; Utsu, 1965). This value is consistent with the global average ($b = 1$), indicating a robust fit (Frohlich and Davis, 1993).

2.2 Spatial Seismicity Rate Estimation

For the sake of applicability, a polygonal curve $\Gamma(Lat, Lon)$ was first defined to pass through the historical epicenters, representing both known and potential earthquake zones. The curve Γ was constructed by interpolating through the historical epicenters and aligning with major subduction interfaces and fault boundaries identified from global tectonic maps. To account for the spatial variability in the number of historical occurrences, as shown in Figure 1b, a spatially varying $a(\Gamma)$ value was derived using one-dimensional Kernel Density Estimation (KDE) along Γ . This approach mitigates data sparsity by smoothing the influence of each historical event over its surrounding area. A Gaussian kernel $f(\Gamma)$ was applied at the projected 1D location (Γ_i) of each filtered historical event:

$$f(\Gamma) = \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{(\Gamma-\Gamma_i)^2}{2\sigma^2}} \quad (2)$$



where a smoothing bandwidth of $\sigma = 500$ km was selected to mitigate the spatial sparsity of the historical catalog (values about that value, i.e., between 400–600 km, yield similar large-scale patterns). Physically, this length scale corresponds to the characteristic rupture dimensions of great subduction zone earthquakes ($M8+$), ensuring that the probabilistic weight is distributed across the entire potentially rupturing fault segment rather than being artificially concentrated at historical epicenters. The continuous curve representing the relative seismicity rate along the potential fault zones is the sum of all kernels. This curve was subsequently normalized to match the total observed annual rate of events above M_c from the modern catalog, so that local variations do not inflate regional seismic productivity, producing an absolute annual rate density for each source point.

The final weight assigned to each source point i is its total annual rate of significant tsunamigenic earthquakes ($M \geq 7.4$), calculated by applying the spatially determined $a(\Gamma)$ from the KDE to the Gutenberg-Richter relationship and integrating over the relevant magnitude bins. This yields a single representative annual rate, λ , which serves as the input likelihood for the tsunami ray-tracing models. The corresponding hazard map, showing the average return period $T = 1/\lambda$, is presented in Figure 2. The resulting hazard map reveals significant spatial heterogeneity in earthquake recurrence. The Kuril-Kamchatka and Japan Trenches in the northwest Pacific, alongside the Peru-Chile Trench in the southeast, emerge as the most seismically active source zones, exhibiting return periods between 100 and 1,000 years (red to orange segments). This creates a dominant ‘hazard dipole’ across the Pacific Basin. Additionally, the Aleutian Trench and the Sumatra-Andaman subduction zone show high recurrence rates, highlighting them as critical sources for transoceanic tsunami generation. In contrast, mid-ocean ridges and transform boundaries generally exhibit longer return periods (blue segments), reflecting their lower potential for generating large tsunamigenic displacements.

In this study we adopt a recurrence-based weighting, though we also examined whether magnitude-energy formulation would alter the resulting coastal exposure patterns. Using the same magnitude bins between $M = 6.5$ and 9.5 , we computed an annualized energy metric Λ_j for each segment j by multiplying each bin’s rate by $E(M) \propto 10^{1.5M}$ and summing across bins. However, since the PTHA implementation employs a single regional b -value and the same magnitude range for all source segments, the Gutenberg–Richter distribution has an identical shape everywhere. Under these assumptions Λ_j reduces to a constant multiple of the recurrence rate ($\Lambda_j = C\lambda_j$), and thus energy-weighted ray-density field would be indistinguishable from the recurrence-weighted field up to a uniform rescaling. For this reason we present the recurrence-based maps, explicitly.

3 Ray Tracing Methodology

To simulate global tsunami propagation and identify regions of energy focusing or shadow zones, we use a numerical wave ray-tracing model based on the geometrical optics approximation. This approach tracks the trajectory of wave energy packets (rays) by solving a set of coupled ordinary differential equations (ODEs) over time. The theoretical framework follows standard formulations for surface gravity waves propagating over variable bathymetry and currents (Halsne et al., 2023).

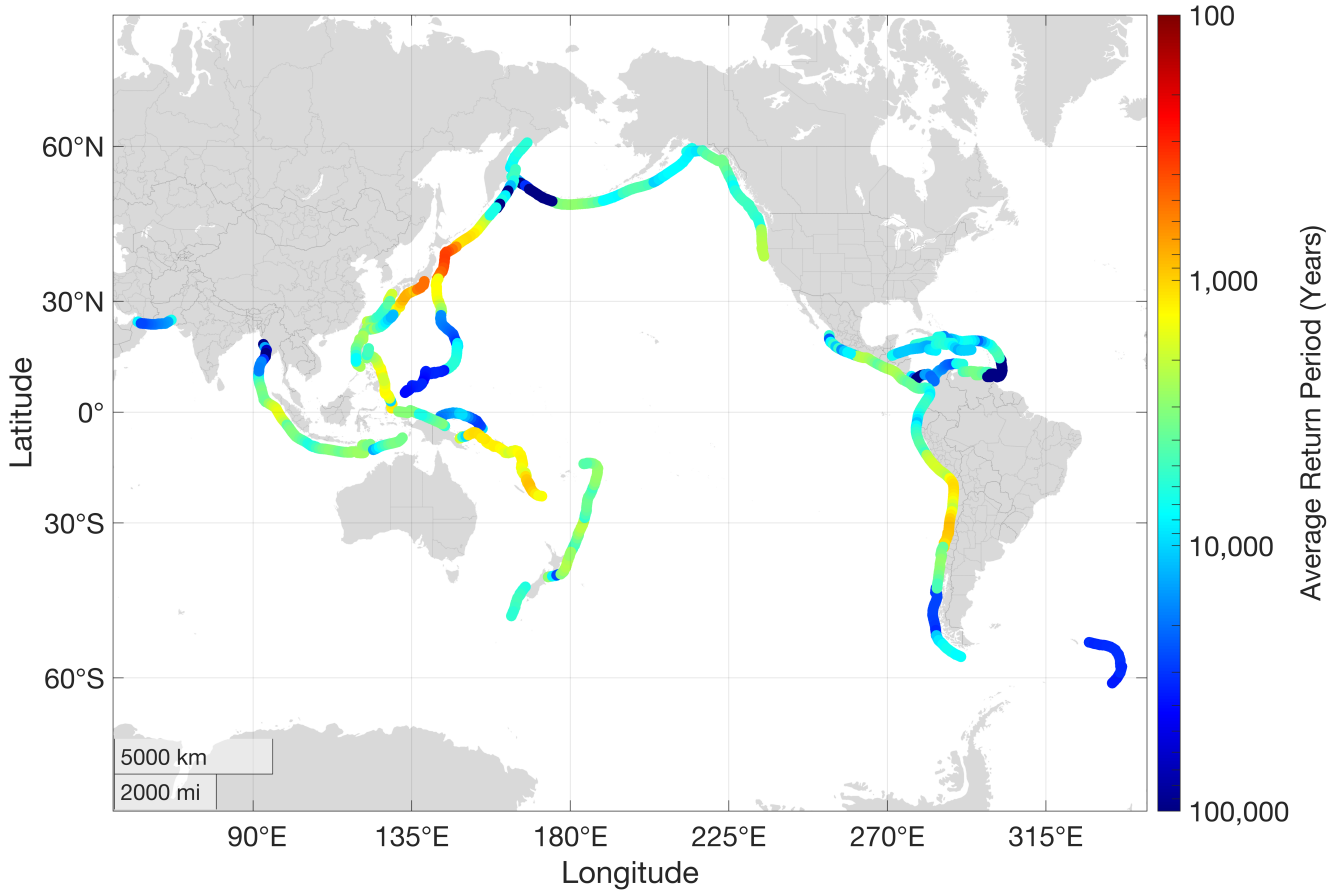


Figure 2. Return period of tsunamigenic earthquakes ($M > 7.4$) along the potential faults, based on historical data analysis, with a spatial resolution of 25 km. Basemap created with Natural Earth data.

3.1 Governing Equations

150 The state of a wave ray is defined by its position vector, $\mathbf{x} = (x, y)$, and wave number vector, $\mathbf{k} = (k_x, k_y)$. Their evolution in time t is governed by:

$$\frac{d\mathbf{x}}{dt} = \mathbf{c}_g + \mathbf{U} \quad (3)$$

$$\frac{d\mathbf{k}}{dt} = -\nabla_h \omega - (\mathbf{k} \cdot \nabla_h) \mathbf{U} \quad (4)$$



Here, $\mathbf{U} = (U, V)$ is the ambient current velocity vector, $\mathbf{c}_g$ is the intrinsic group velocity vector, and ω is the intrinsic
155 angular frequency of the wave. For far-field tsunami applications, ambient currents are negligible compared to the wave speed,
so we set $\mathbf{U} = 0$ in Equations 3–4.

The angular frequency ω is related to the wave number magnitude $k = |\mathbf{k}| = \sqrt{k_x^2 + k_y^2}$ and local water depth d through the
linear dispersion relation:

$$\omega^2 = gk \tanh(kd) \quad (5)$$

160 Wave refraction is governed by the term $-\nabla_h \omega$ in Equation 4 (where $\mathbf{U} = 0$). Since ω depends on both k and d , its horizontal
gradient is primarily driven by bathymetric variations:

$$\nabla_h \omega = \frac{\partial \omega}{\partial d} \nabla_h d \quad (6)$$

and because no diffraction term is included here, rays cannot reproduce energy leakage around obstacles. This shows that
changes in the wave number vector, and thus the propagation direction, are directly proportional to the local sea-floor gradient,
165 $\nabla_h d$, which is the main mechanism for tsunami refraction across ocean basins.

3.2 Numerical Implementation

The system of ODEs (Equations 3 and 4) is solved numerically to trace each ray's trajectory using a fourth-order Runge-Kutta
scheme. Rays propagate over a global, unstructured triangular mesh with approximately 1.3 million nodes and 2.6 million
elements, with spatial resolution varying from 10 to 28 km. The mesh is generated based on the shallow-water group velocity,
170 ensuring that tsunami wavelengths are adequately resolved. Bathymetric data are sourced from 2025 General Bathymetric
Chart of the Oceans dataset (GEBCO, 2025) with 1 arc-second resolution. Using a time step of 180 s and Courant-Friedrichs-
Lewy CFL < 1 , the depth-dependent resolution is set as the product of the time step and local group velocity, ensuring that no
ray travels more than one element per time step.

At each time step, environmental parameters are evaluated dynamically, as rays can lie anywhere within a mesh element.
175 Water depth at a ray's latitude-longitude location is computed using barycentric interpolation from the nodal values of the
containing element. The bathymetric gradient, $\nabla_h d$, which drives wave refraction, is precomputed for all elements to improve
computational efficiency.

3.3 Numerical Simulations

Rays are initialized along potential tsunami-generating fault lines, shown in Figure 2, at 25 km intervals. Each ray is assigned
180 a characteristic tsunami period ranging from 15 minutes to 3 hours, with the initial propagation direction set perpendicular to
the fault segment and oriented oceanward. A ray is terminated if it reaches land (where water depth becomes zero or negative)
or enters a user-defined shallow coastal zone (500 m depth). This cutoff is imposed to exclude the complex nearshore region



where nonlinear shoaling dominates and where strong refraction often leads to ray crossing (caustics), rendering the standard geometrical optics approximation insufficient. In total, 9,000 rays were released, and the simulation was run for 24 hours, sufficient for all rays to reach a termination criterion. Upon termination, the density of ray impacts along the coastline is calculated. This metric, referred to as the normalized ray termination count (ranging from 0 to 1), serves as a geometric proxy for relative coastal tsunami wave amplitude, effectively mapping regions of energy convergence (focusing) and divergence (shadowing). This framework allows efficient and accurate simulation of tsunami propagation across complex global bathymetry, illustrating how basin geometry controls wave energy distribution. The simulations were performed on a 32-core Mac Studio with 512 GB of unified memory. The code is parallelized, and since each ray is treated independently, the 24-hour simulation completed in approximately 12 hours.

This ray-tracing approach captures tsunami hazard primarily for transoceanic propagation from the source across the basin to distant locations. Hazards in the immediate vicinity of the earthquake are not considered in this study, as our focus is on the effects of ocean-basin geometry on tsunami travel; near-source tsunamis may indeed be more catastrophic, but they fall outside the scope of this work.

To systematically examine how source geometry, recurrence intervals, and bathymetric refraction shape global tsunami exposure, we designed four targeted numerical experiments. Each scenario isolates a fundamental driver of tsunami propagation: (i) fault geometry, which controls the initial azimuth and directional bias of energy release; (ii) variable bathymetry, which refracts and redirects wave trajectories across the basin; and (iii) probabilistic weighting, which modulates hazard intensity based on earthquake return periods. Figure 3 summarizes the outcomes, where basin-scale ray density is shown using a white-to-blue scale, and coastal focusing is highlighted by a green–yellow–red scale. All results are normalized by the global maximum to enable direct comparison across experiments.

The left panels (Figures 3a-b) adopt a constant-depth approximation, forcing rays to follow great circle paths (GC) and, by design, removing any effect of bathymetric refraction. This configuration exposes the sole influence of fault geometry and position, effectively reducing the ocean basin to a two-dimensional line-of-sight system. Under these conditions, we observe a striking artifact: a highly energetic corridor extending across the Pacific Basin, originating from the Kuril–Kamchatka and Japan trenches. This direct projection leads to an exaggerated and unrealistic signature of exposure along the northeast coast of Australia, Papua New Guinea, and the Solomon Islands, as well as a broad, nearly uniform zone of impact along South America. Panel (a), using uniform ray release, overemphasizes the role of smaller fault systems; Panel (b) incorporates the probabilistic weights (λ) from Section 2, refining the magnitude but still retaining the unrealistic linear propagation patterns inherent to the constant-depth assumption.

A very different picture emerges in the right panels (Figures 3c-d), where realistic bathymetry is introduced. Here, refraction and scattering fundamentally reorganize the tsunami wavefield. The artificial exposure corridor toward Northeast Australia is dismantled almost entirely as rays encounter the complex topography of the Southwest Pacific—namely the Melanesian Arc and the Solomon Rise, where strong refractive scattering disrupts coherent wavefronts. This bathymetric shielding drastically reduces predicted hazard levels along the eastern Australian coastline. In contrast, topographic structures in the North Pacific, such as the Emperor Seamount Chain and the Mendocino Fracture Zone, act as waveguides, channeling energy toward North

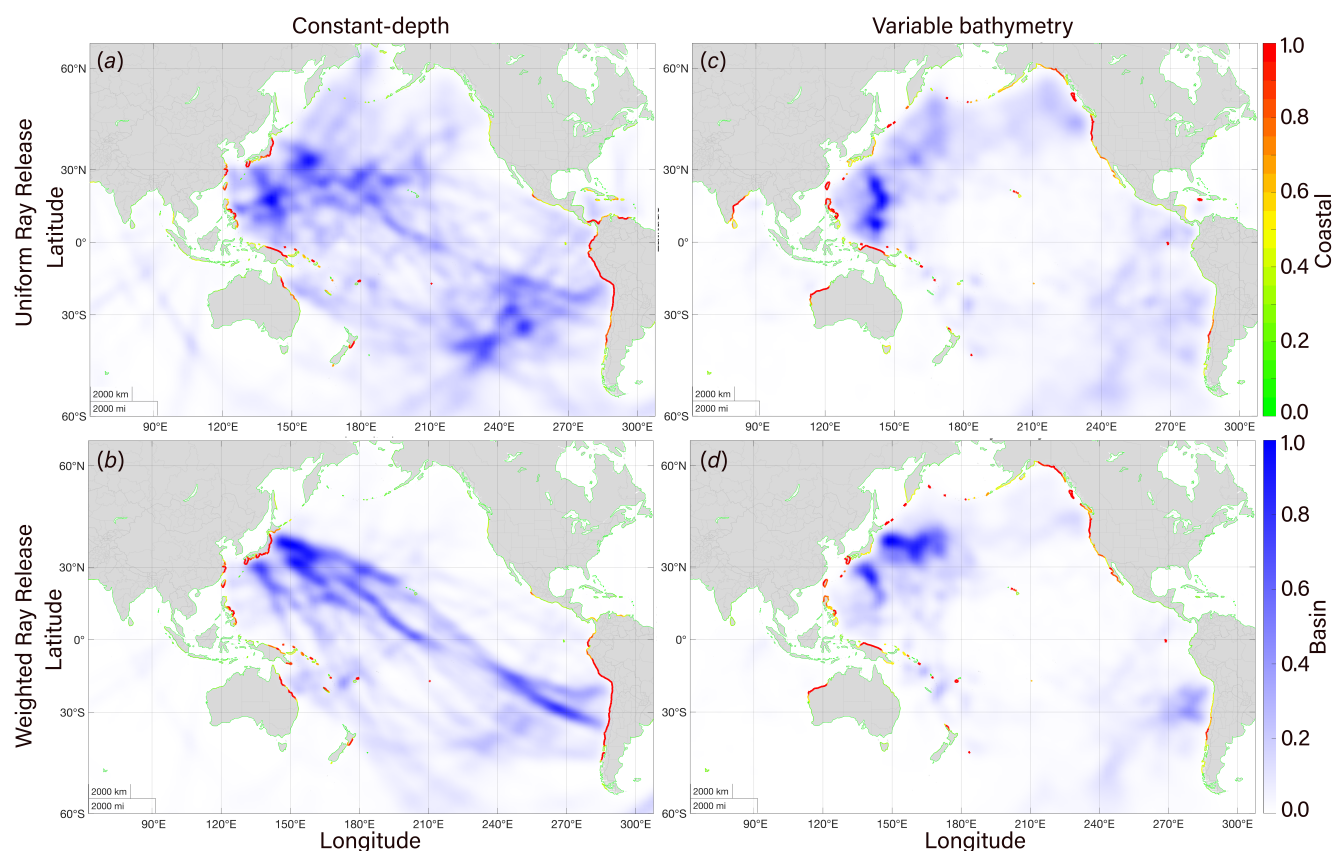


Figure 3. Basin-wide ray density and coastal tsunami hazard for 9,000 tsunami rays released along potential fault zones (shown in Figure 2). Panels (a,b) represent constant-depth cases, highlighting the effects of fault location and orientation, while panels (c,d) incorporate variable bathymetry to show the combined influence of seafloor geometry and fault configuration. The top row shows uniformly released rays, and the bottom row applies probabilistic weighting (using the annual rate parameter λ from Section 2) based on return period derived from the Gutenberg–Richter relation. The ocean-floor heatmap (white to blue) illustrates ray convergence and geometric focusing, and coastline colors (green–yellow–red, normalized 0–1) indicate relative tsunami hazard, with redder areas denoting higher exposure. Basemap created with Natural Earth data.



America. Relative to the broad energy field in Panel (b), the results in Panel (d) reveal a sharpened, high-intensity beam targeting the Pacific Northwest and Northern California.

220 Panel (d) represents the most complete hazard characterization, combining realistic bathymetry with the probabilistic source weighting (λ) derived in Section 2. By modulating the intensity of each ray based on its source's annual occurrence rate (λ), this configuration filters out low-probability contributions seen in Panel (c) and exposes the dominant corridors of trans-oceanic energy. Notably, it reveals a striking reciprocal hazard pathway between South America and East Asia: just as the Kuril–Kamchatka system preferentially feeds energy toward Chile, the Peru–Chile trench returns a concentrated ray field
 225 toward Japan and the Philippines. Additionally, the model identifies a pronounced shadow zone in the Southeast Pacific—west of the East Pacific Rise—where energy is notably absent. This suggests that the ridge system acts as a large-scale defocusing boundary. Finally, unlike the uniform scenario, the probabilistic approach intensifies the signal over the Bay of Bengal and the Indonesian archipelago, where high recurrence rates of tsunamigenic earthquakes lead to elevated hazard levels that would otherwise be underrepresented.

230 4 M8.8 Kamchatka Peninsula event

On July 29, 2025, at 23:24 UTC, a moment magnitude (M_w) 8.8 earthquake struck off the eastern coast of Russia's Kamchatka Peninsula. The epicenter was located at 52.51°N, 160.32°E, approximately 136 km east-southeast of Petropavlovsk-Kamchatsky, at a depth of 35 km, according to the United States Geological Survey (USGS). The earthquake resulted from thrust faulting along the Kuril-Kamchatka subduction zone, where the Pacific plate subducts beneath the North American
 235 (Okhotsk) plate. This event ranks among the largest earthquakes globally since 2011 and is one of the six largest recorded in the modern instrumental era.

The earthquake generated a trans-Pacific tsunami, with maximum run-up heights of about 3 m in Severo-Kurilsk, Russia, and up to 1.2 m in Hawaii. While initial warnings indicated potentially higher impacts, the remote location and rapid alert system limited casualties and damage. One indirect fatality was reported in Japan, and several injuries occurred. In Kamchatka
 240 Krai, moderate damage was observed, including power outages and structural impacts in Petropavlovsk-Kamchatsky. This event underscores the potential of large subduction zone earthquakes in the North Pacific to generate widespread trans-oceanic tsunami hazards and highlights the importance of early warning systems for coastal risk mitigation.

The initial condition for the tsunami propagation model FUNWAVE is the residual vertical seafloor displacement field generated using the elastic half-space model of Okada (1985). For the M8.8 Kamchatka Peninsula event, this study utilizes
 245 two distinct source models, hereinafter referred to as the NOAA and USGS scenarios. The NOAA scenario is not derived from direct seismic measurements, but from an inversion of tsunami observations recorded at DART buoys. This approach uses the Method of Splitting Tsunami (MOST) model, which involves matching real-time observations to a linear combination of pre-computed tsunami waveforms from unit sources (Titov et al., 2005). The resulting source model for this event consists of nine sub-faults, with characteristics shown in Table 1. In contrast, the USGS scenario is based on seismological inversion using
 250 ground motion data and finite-fault analysis, resulting in a more complex source defined by 345 sub-faults (Hayes, 2017). The



NOAA solution commonly performs better for tsunami propagation because it assimilates offshore DART waveforms. The vertical coseismic displacement fields for both scenarios are illustrated in Figure 4.

To quantitatively compare these sources and estimate key tsunami parameters, a standardized method is applied to each deformation field. First, the primary generation area is identified by a polygon enclosing all points where the absolute displacement exceeds a 10% threshold of the maximum deformation. An oriented bounding box is then fitted to this polygon, yielding the source's effective length (L_{eff}), effective width (W_{eff}), and average strike. Subsequently, a single characteristic length (L_c) is derived as the hypotenuse of the effective dimensions ($L_c = \sqrt{L_{eff}^2 + W_{eff}^2}$). This geometric proxy serves as a robust estimate for the dominant initial wavelength, explicitly linking the spatial extent of the seafloor uplift to the frequency content of the generated wave. This characteristic length, combined with the average ocean depth across the source region, is then applied to the linear dispersion relation to calculate the tsunami's characteristic wave period (Geist, 2002). Table 2 summarizes these effective fault and tsunami parameters for both scenarios. For validation, these model-derived periods are later compared against the wave period determined from an analysis of the observed DART buoy recordings for this event.

Table 1. Fault parameters for NOAA scenario, with length 100 km, width 50 km, and rake 90°

Lon ($^\circ$)	Lat ($^\circ$)	Depth (km)	Strike ($^\circ$)	Dip ($^\circ$)	Slip (m)
160.2771	52.2889	38.2502	218	29	3.9036
158.8796	51.8229	62.4902	218	29	8.3453
158.5230	50.8438	38.2502	214	29	11.4335
159.0456	50.6201	15.5655	214	25	1.0997
158.0060	51.0634	62.4902	214	29	4.1837
157.7104	50.1261	40.5760	218	31	6.2835
158.1906	49.8844	16.3498	218	27	1.8474
157.2360	50.3631	66.3260	218	31	5.9568
156.8407	49.4333	40.5760	220	31	5.7094

Table 2. Comparison of NOAA and USGS fault scenarios

Parameter	NOAA	USGS
No. of sub-faults	9	345
sub-faults dimensions (km)	100×50	30×15
Fault effective length (km)	520	450
Fault effective width (km)	140	123
Characteristic length (km)	540	465
Mean depth (m)	2880	2960
Average strike ($^\circ$)	217	218
Wave period (s)	3200	2700

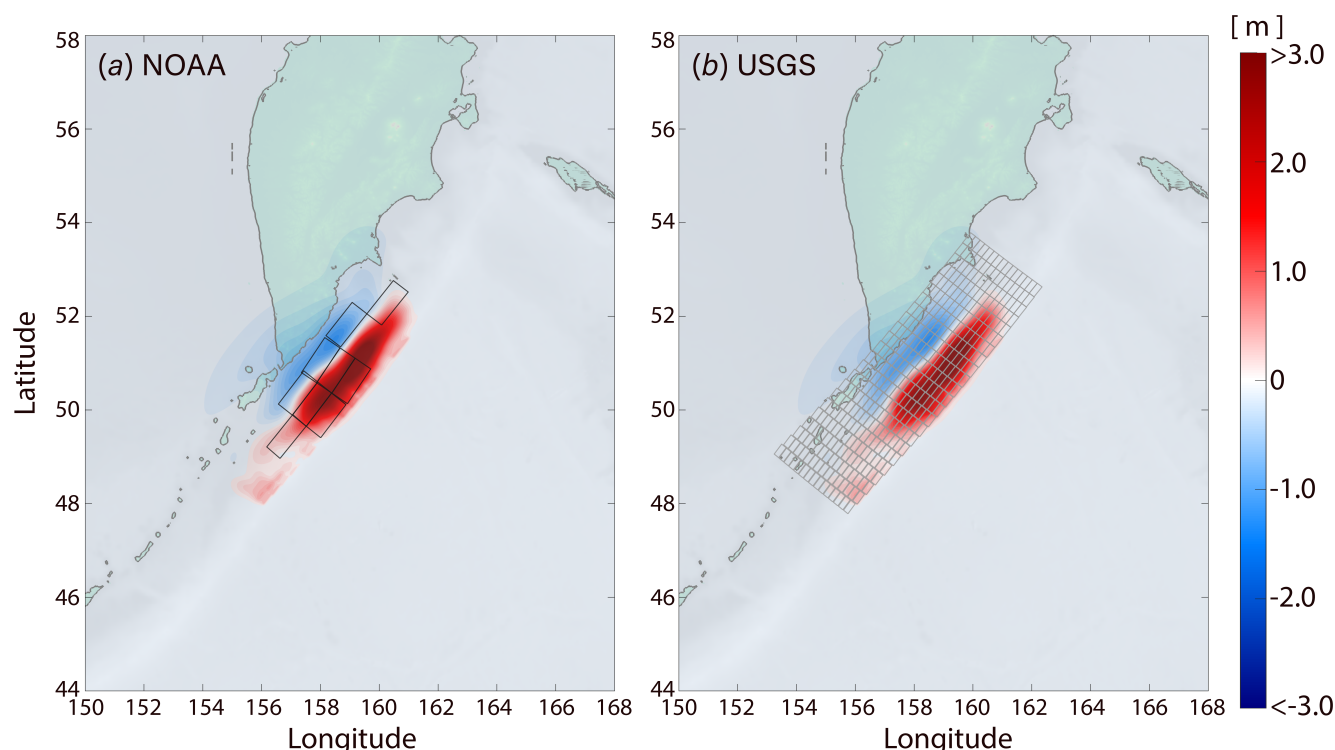


Figure 4. Residual vertical component of bed deformation for two scenarios based on inversion performed by a) NOAA with 9 sub-faults with 50×100 km dimension and b) USGS with 345 sub-faults with 15×30 km dimension.

4.1 High fidelity modeling (FUNWAVE)

For the simulation of tsunami wave propagation, we use the Boussinesq-type wave model, FUNWAVE, in spherical coordinates (Kirby et al., 2013). The model has been validated against a large set of analytical, laboratory, and field benchmarks as part of the development of tsunami hazard maps for the US East Coast (Tehranirad et al., 2011). An optimized MPI parallel implementation of FUNWAVE was developed, which has highly scalable algorithms, with a typical parallel scaling efficiency of more than 90% of the number of cores in a typical medium-sized computer cluster. This makes it possible to run the model over large ocean basin-scale grids with a sufficiently fine resolution.

The grid used in FUNWAVE simulations was developed from GEBCO (2025), which was downsampled from a resolution of 1 arc-second to 4 arc-minutes and cropped to focus on the Pacific Ocean, resulting in a final rectilinear grid comprising over 5 million points. Simulations were executed on an AMD EPYC 7H12 processor with a 2.6 GHz 64-core (128-thread) architecture, requiring approximately 50 minutes of real time to simulate 32 hours of tsunami propagation. To mitigate wetting and drying numerical artifacts along the coastline while preserving the steep bathymetric gradients of the Kuril-Kamchatka subduction zone essential for accurate wave generation, a spatially selective smoothing approach was adopted. A ramp function (Figure 6) was constructed around the 10-meter depth contour to linearly transition from the original bathymetry in the deep ocean to a

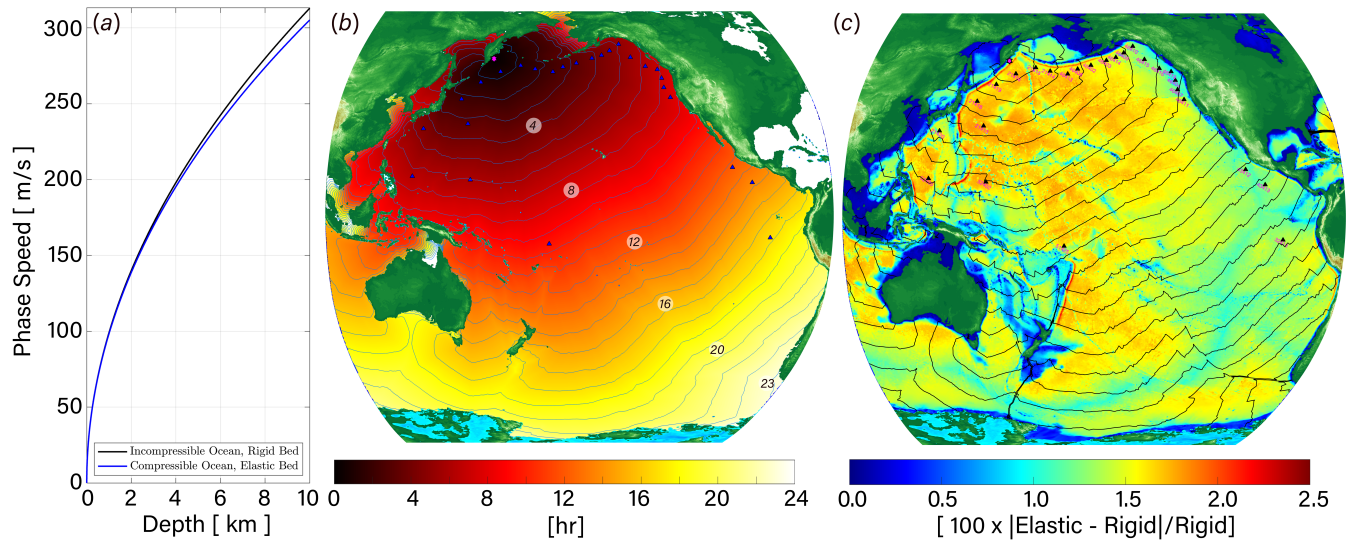


Figure 5. (a) Phase speed from the classic dispersion relation for an incompressible ocean over a rigid bottom (black) and for a compressible ocean with an elastic bottom and background density (blue); (b) Surface gravity wave travel time derived from the blue curve in panel (a); black contours show travel time at 1-hour intervals; (c) Percentage reduction in phase speed between the black and blue curves in panel (a); black contours show the difference in travel time between the two dispersion relations at 1-minute intervals.

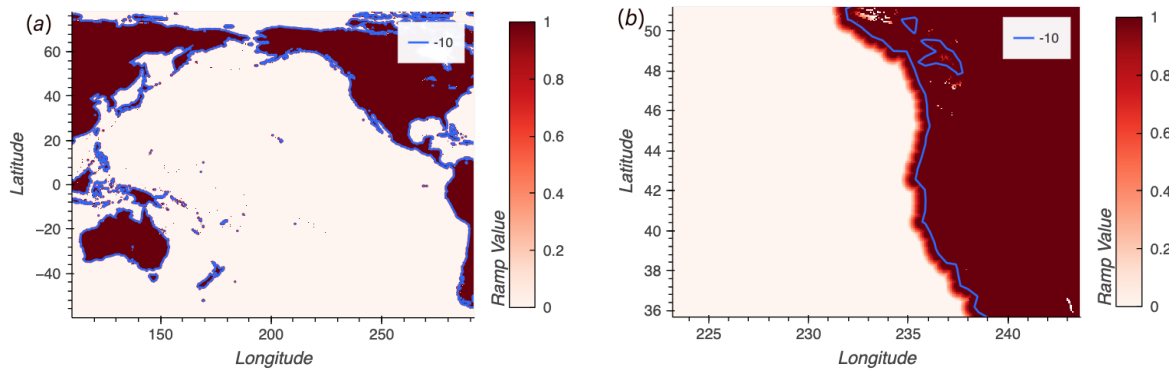


Figure 6. (a) Ramp function used to smooth transition the original grid to the Gaussian smooth grid. (b) Enlarged view of the ramp function along the United State's West Coast. Blue contour line denotes the 10 meter depth contour in both panels.

Gaussian-smoothed grid in shallow coastal waters. This approach effectively ensures numerical stability in the nearshore region without compromising the bathymetric fidelity at the earthquake epicenter. Additionally, sensitivity simulations conducted on higher resolution 8 and 16 arc-minute grids yielded negligible differences in results, confirming that the chosen 4 arc-minute resolution is adequate for resolving the initial seafloor displacement and modeling transoceanic tsunami propagation.

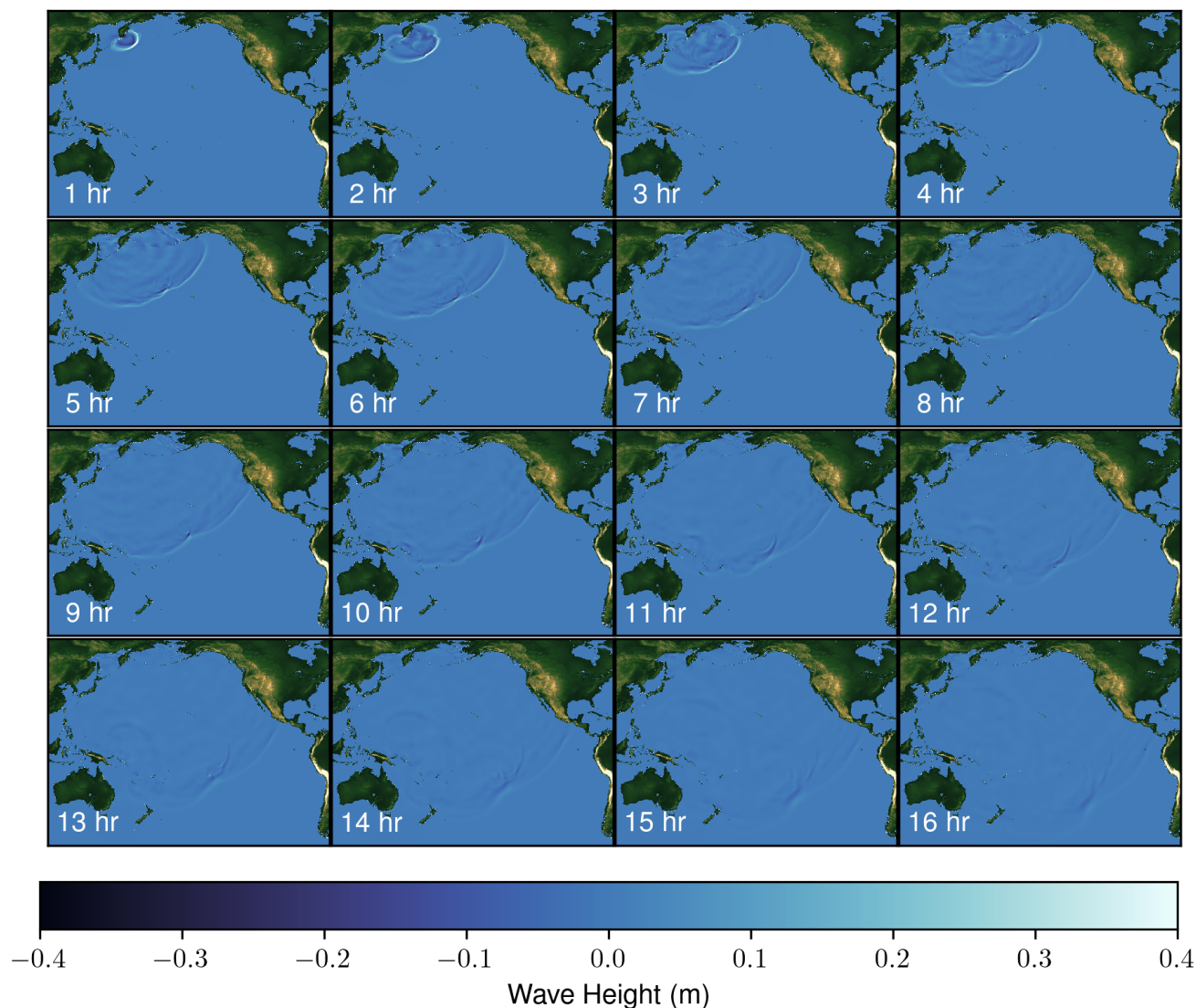


Figure 7. Free surface height (η) from FUNWAVE simulation initialized with bed deformation from NOAA scenario. Simulation results are shown at 1-hour intervals across the panels.

For both cases, NOAA and USGS, FUNWAVE simulations were performed using the bed deformation as the initial free surface water height. Figure 7 depicts the time history of generation and propagation of tsunami waves in the computational domain for the NOAA case.



4.1.1 Phase lag correction

285 In FUNWAVE, the ocean is represented as incompressible, without background density, and over a rigid bottom. This as-
 sumption produces faster phase speeds and earlier arrivals, with the effect amplified at distant stations. Without correction,
 this theoretical limitation results in large temporal errors, representing a major drawback of standard incompressible models
 for far-field hazard assessment. To correct this bias, the lag was quantified and applied to the model outputs. Crucially, this
 correction is implemented strictly as a kinematic time-shift to align arrival times; it does not adjust the hydrodynamic wave
 290 amplitudes calculated by the model.

Tsunami periods were first estimated from the characteristic fault length (465–540 km) and mean depth (3000 m), yielding
 values of 2700–3200 s for the NOAA and USGS scenarios (Table 2). To validate these estimates, a 12-h observational window
 at DART stations was analyzed (Fig. 8b), indicating an average period of 3600 s. Phase speeds were then calculated using (i) the
 classical dispersion relation under incompressibility and rigid-bottom assumptions, and (ii) a compressible-ocean formulation
 295 with elastic bed and background density (Abdolali et al., 2019), as shown in Figure 5a. These values were incorporated into
 the shortest-path framework to compute arrival times (Kadri et al., 2025).

Figure 5b presents tsunami travel times derived from Dijkstra’s algorithm (Kadri et al., 2025), which operates on graphs
 with non-negative edge weights, employing a greedy strategy to update shortest-path distances from the source node while
 maintaining a set of visited nodes and a priority queue. The travel times from solution (ii) are shown with 1-h contour intervals
 300 across the Pacific basin; DART buoy locations are indicated by rectangles. Figure 5c shows the phase speed from the full
 solution (ii) in the background, with contours representing the difference in arrival times between the two formulations (in
 minutes). These differences (listed in 8c) at the DART sites were used to shift the FUNWAVE outputs, aligning modeled
 arrivals with observations (Fig. 8a).

Statistical analysis of phase-lag–corrected FUNWAVE outputs at DART stations demonstrates that the model effectively
 305 captures the tsunami signals generated by both source scenarios, with superior performance achieved using the NOAA fault
 configuration. The NOAA-forced simulation yields a Root Mean Square Error (RMSE) of 0.057, approximately 35% lower
 than the USGS RMSE of 0.088, indicating a substantially smaller overall prediction error. Furthermore, the NOAA solution
 exhibits higher model fidelity, characterized by a Skill Factor of 0.955 and a low Scatter Index (SI) of 0.151, compared to the
 USGS scenario, which produced a Skill Factor of 0.915 and a significantly larger SI of 0.380.

310 4.2 Spatial Hazard Assessment

With the hydrodynamic model successfully validated against DART observations, we now evaluate the spatial distribution of
 tsunami energy across the Pacific basin. This step bridges the probabilistic and geometric frameworks outlined in Sections 2
 and 3 with the deterministic, high-fidelity simulation of the 2025 Kamchatka Peninsula event.

To evaluate the predictive capability of the ray-tracing framework, the model was initialized using the fault parameters of
 315 the Kamchatka event (NOAA scenario) listed in Table 2. Rays were released along the fault line using a characteristic wave
 period of 3200 s and a fault length of 540 km, with a strike of 217° . Rays were emitted perpendicular to the fault orientation,

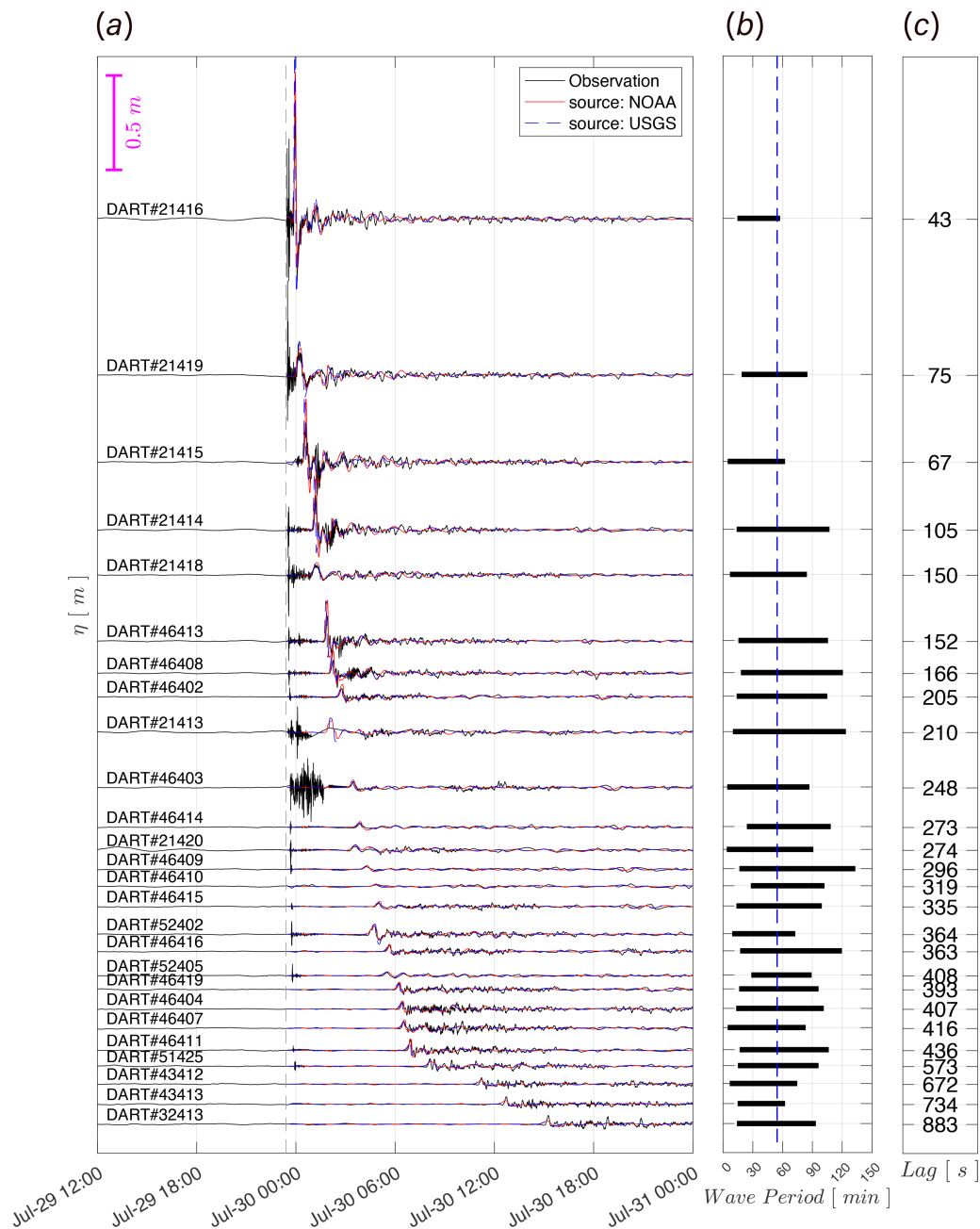


Figure 8. (a) Time series at DART observatories (black), with FUNWAVE simulations forced by the NOAA fault scenario (red) and the USGS scenario (blue). Stations are ordered by distance from the epicenter (magenta star in Fig. 5). The locations of the DART buoys are shown in Fig. 5. The vertical dashed line marks the earthquake origin time. (b) Estimated range of tsunami wave periods at all stations. The vertical dashed blue line indicates the overall mean period (~60 min), used in the phase speed calculation. (c) Time lag between computed arrivals based on the standard dispersion relation and those incorporating ocean compressibility, Earth elasticity, and background density. The FUNWAVE results in panel (a) are shifted according to the values in panel (c).



enabling a realistic representation of the initial radiation pattern, and were then tracked across the Pacific basin to identify convergence zones. The resulting normalized ray termination counts are shown in Figure 9a. Note that ray-based shadow zones appear sharper because diffractive spreading is absent in geometric optics. The simulation reveals clear corridors of energy focusing. In the near field, high ray densities emerge along the Aleutian Islands and Alaska, primarily governed by the fault orientation and source proximity. In the far field, bathymetric refraction organizes tsunami propagation into a dominant southeastward beam that first targets the Hawaiian Islands and then continues into the Southeast Pacific, ultimately forming a coherent refractive corridor that extends southward toward the coast of Chile. A second beam projects eastward toward the North American coast, notably targeting Washington, Oregon, and Northern California.

These geometric patterns are strongly supported by the full hydrodynamic simulation. Figure 9b shows the maximum wave amplitude envelope computed by FUNWAVE. The spatial distribution closely aligns with the convergence zones identified in panel a, while also capturing additional physical processes absent in the ray tracing model. First, the ray-based simulation produces sharp shadow zones behind island chains (e.g., southeast of Hawaii), an expected consequence of its geometrical optics approximation. In contrast, FUNWAVE shows softer gradients, where diffraction allows partial energy penetration into these shadow regions. Second, the hydrodynamic solution reveals faint concentric ripples radiating from the continental margins—reflected energy that is naturally captured in FUNWAVE but purposely omitted in the ray-tracing model, where rays terminate upon coastal impact.

While a strong qualitative agreement is visually evident in the spatial alignment of energy corridors shown in Figure 9, we further evaluated the model's performance statistically. To quantify the consistency between the geometric proxy and the hydrodynamic simulation, we extracted spatially co-located pairs of maximum wave amplitude from the FUNWAVE simulation and normalized ray density along the transoceanic coastlines, excluding the near-field deformation zone where finite-fault effects dominate. Spearman's rank correlation coefficient (ρ) was selected to evaluate the monotonic relationship between the geometric proxy and the physical wave heights, assessing the model's ability to correctly rank hazard intensities rather than assuming linear proportionality. The analysis yields a correlation of $\rho = 0.66$, indicating a substantial positive relationship. This metric confirms that, despite the omission of diffraction and non-linear integration in the geometric optics approximation, the ray-tracing framework reliably captures the dominant spatial hierarchy of transoceanic energy distribution.

Despite these differences, both models consistently identify the primary energy corridors toward Hawaii and the U.S. West Coast. It is worth emphasizing that while FUNWAVE resolves extreme wave heights near the source (e.g., Russia and the Kuril Islands), the ray tracing approach does not attempt to capture near-field, finite-fault deformation effects; its strength lies in resolving transoceanic propagation pathways with high computational efficiency.

Finally, these modeled hotspots are corroborated by in-situ observations. Figure 10 presents the maximum water levels recorded at NOAA tide gauge stations. The observational record exhibits strong agreement with both the ray tracing and hydrodynamic models. The highest amplitudes (red and orange markers) occur precisely where both frameworks predicted energy focusing—along the Hawaiian Islands and the U.S. West Coast. Importantly, the secondary southern beam identified in both the ray-tracing solution (Figure 9a) and the hydrodynamic envelope (Figure 9b) is confirmed by an elevated water level at a gauge in the Southeast Pacific (Figure 10), demonstrating the model's ability to resolve narrow, refractive transoceanic pathways over

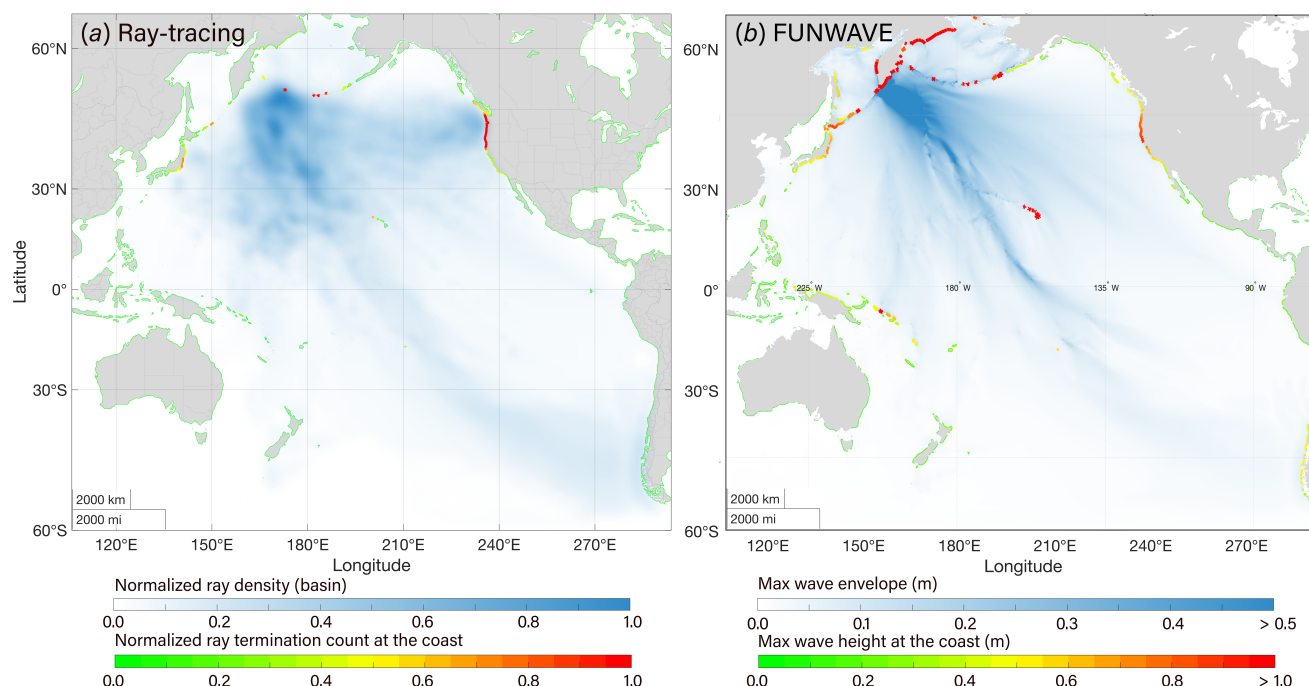


Figure 9. (a) Basin-wide ray density and coastal tsunami hazard derived from the ray-tracing model; (b) Maximum free-surface elevations from FUNWAVE simulations for the 2025 Kamchatka Peninsula event, with the basin-wide field shown using the white–blue colormap and coastline segments using the green–yellow–red colormap. Basemap created with Natural Earth data.

great distances. Collectively, these results show that when informed by accurate source mechanics, the ray-tracing framework serves as a robust and computationally efficient proxy for identifying far-field coastal exposure and quantifying basin-scale tsunami hazard.

355 5 Conclusions

This study introduced a hybrid probabilistic–geometric framework, intended for rapid farfield hazard screening rather than local inundation modeling, that bridges the gap between statistical seismic hazard assessment and physically grounded tsunami propagation modeling. By integrating earthquake recurrence statistics derived from the Gutenberg–Richter relation with basin-scale ray tracing, the method efficiently maps global patterns of energy convergence and identifies coastlines most susceptible to transoceanic tsunami exposure. This approach provides a rapid, computationally scalable alternative to full hydrodynamic ensemble modeling, making it suitable for global screening and early-stage hazard prioritization.

The framework was rigorously validated using the 2025 M8.8 Kamchatka Peninsula earthquake as a benchmark case. Phase-corrected FUNWAVE simulations showed strong agreement with in-situ DART and tide-gauge observations, confirming that the hydrodynamic model, when corrected for compressibility, earth elasticity and background density, reproduced the key

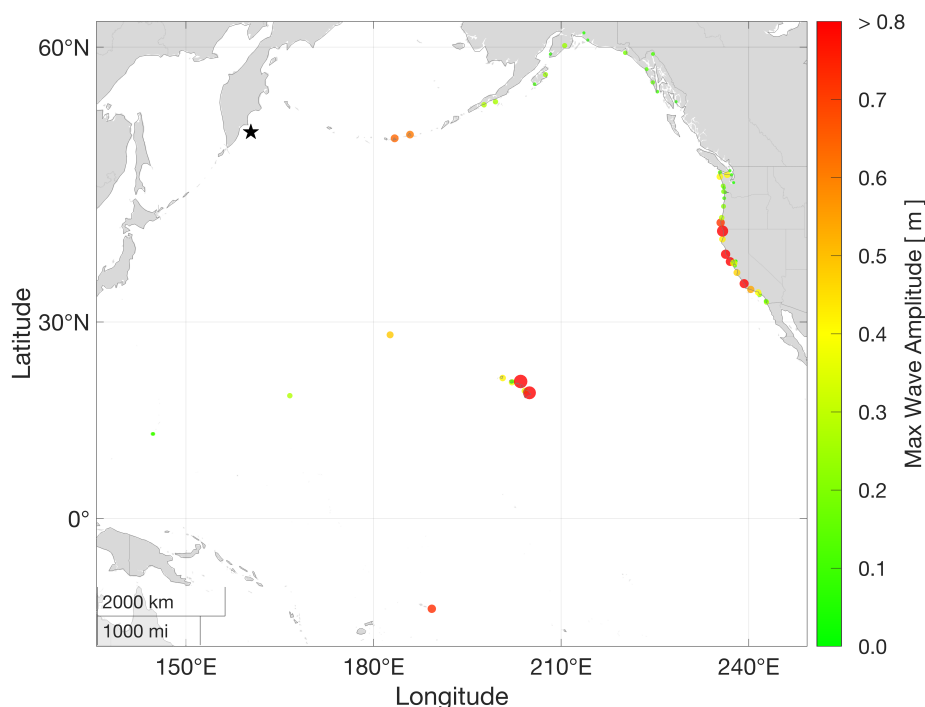


Figure 10. Maximum observed water levels at NOAA tide gauge stations along the coastline. Basemap created with Natural Earth data.

365 timing and amplitude characteristics of the event. Building on this foundation, the ray-tracing model, initialized with the
 optimized NOAA source parameters, successfully resolved the dominant transoceanic energy trajectories. Both the ray tracing
 and hydrodynamic models identified the primary focusing pathway toward Hawaii and the U.S. West Coast, as well as the
 refraction-driven beam directed toward Chile.

The comparative analysis highlighted both the utility and the physical limitations of the geometric approach. While the
 370 ray-tracing model accurately predicted the location of far-field hotspots, it produced sharp shadow zones that neglected the
 diffraction effects captured by the weakly dispersive hydrodynamic model. Despite this approximation, the spatial alignment
 of maximum energy envelopes across observations, FUNWAVE simulations, and ray clusters, quantified by a Spearman corre-
 lation of $\rho = 0.66$, demonstrates that bathymetric refraction is the primary mechanism governing basin-scale tsunami intensity
 distribution.

375 Ray tracing, weighted by recurrence-based probability, directly addresses the need for scalable hazard assessment. By fil-
 tering theoretical energy exposure through the lens of recurrence likelihood, the model provides a prioritized map of coastal
 regions where tsunami impacts are both physically focused and statistically probable. This combination offers a robust prac-
 tical utility for coastal resilience, as consistently identified along high-energy refraction pathways can be flagged for focused
 vulnerability assessment and the allocation of high-fidelity modeling resources. To date, many new construction initiatives
 380 along the coastlines require design analysis against both the extreme weather hazards and seismic-generated wave flooding



events. Frameworks like those described in this manuscript can give rise to improved operational utility and creation of a single pane of glass, or a system of systems for hazard mitigation. In summary, this work demonstrates that a probabilistic–geometric approach serves as a defensible and efficient proxy for global tsunami hazard assessment, guiding decision-makers toward the communities facing the highest likelihood of future transoceanic impact.

385 *Code availability.* The FUNWAVE-TVD model code used in this study is publicly available on GitHub at <https://github.com/fengyanshi/FUNWAVE-TVD>. The data used to produce the results of this study are available from the corresponding author upon request.

Author contributions. AA: Conceptualization, Methodology, Software (Ray tracing model development), Validation, Formal analysis, Investigation, Data Curation, Supervision, Visualization, and Writing – original draft. ML: Investigation, FUNWAVE simulation, Visualization, 390 and Writing – review & editing. UK: Methodology, Investigation and Writing – review & editing. MM: Investigation, FUNWAVE simulation and Writing – review & editing. MF: Investigation, Software (Tsunami Travel Time/GREAT) and Writing – review & editing. FS: Investigation, Software (FUNWAVE model development) and Writing – review & editing.

Competing interests. The authors declare that they have no competing interests

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