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Special Collection:

Coupling Processes from Space to Earth

Y. Kaneko and P. A. Inchin contributed equally to this work.

Key Points:

- 3D simulations of earthquake atmospheric coupling reveal how source characteristics influence upper-atmosphere acoustic signals
- Including nonlinear evolution of upward acoustic waves (AWs) into shocks is key to accurate earthquake source characterization
- Supershear earthquakes generate earlier, distinct AWs compared to subshear earthquakes

Supporting Information:

Supporting Information may be found in the online version of this article.

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Acoustic Wave Signatures of Earthquake Rupture Dynamics in the Upper Atmosphere

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Abstract We perform three-dimensional coupled earthquake-atmosphere numerical simulations that integrate dynamic rupture, seismic wave propagation, and a compressible nonlinear atmospheric model to investigate how earthquake source parameters influence acoustic wave (AW) characteristics at 100–300 km altitude in the thermosphere. Specifically, we examine the effects of magnitude, fault type, and rupture speed by simulating a range of rupture scenarios, including sub- and supershear ruptures, normal and thrust faulting, heterogeneous ruptures, and tsunami earthquakes. Supershear ruptures generate AWs with earlier arrival times and distinctive signal shapes compared to subshear events. Normal-faulting earthquakes produce much weaker AW amplitudes due to rarefaction waves at the surface evolving into shock N-waves, contrasting with the stronger compressive AWs from thrust earthquakes. Fault heterogeneity strongly affects AWs in the lower atmosphere, but its influence diminishes in the upper atmosphere. Tsunami earthquakes yield AWs with similar periods but 20%–50% smaller amplitudes than thrust earthquakes of the same moment magnitude, offering a potential diagnostic feature. Our results show that the nonlinear evolution of AWs precludes straightforward comparison between surface and upper-atmosphere signals, making proper modeling of upper-atmospheric shock properties essential for reliable interpretation. We further corroborate that energy magnitude of an earthquake, rather than moment magnitude, primarily controls AW amplitude in the upper atmosphere. These findings underscore the diagnostic potential of upper-atmosphere observations, such as Global Navigation Satellite System signals, for constraining earthquake source characteristics, improving seismic monitoring, and advancing our understanding of earthquake-atmosphere interactions.

Plain Language Summary We use advanced 3D computer simulations to study how different types of earthquakes send acoustic waves into the upper atmosphere (100–300 km altitude). These waves can be detected by satellites or remote sensing instruments and provide extra information about the earthquake source. Our results show that fast “supershear” ruptures create earlier and distinct signals, while normal-faulting earthquakes produce much weaker signals than thrust earthquakes. We also demonstrate that tsunami earthquakes generate waves with similar periods but up to 50% smaller amplitudes than thrust earthquakes of the same size, making them potentially distinguishable. Fault-slip complexity strongly influences signals near the ground but has little effect higher up. Overall, the strength of upper-atmospheric signals depends more on radiated earthquake energy than on earthquake size as measured by moment magnitude. These findings show that monitoring the upper atmosphere can improve earthquake detection and characterization.

1. Introduction

Earthquakes result in the generation of acoustic waves (AWs) in the atmosphere (e.g., Press & Harkrider, 1962). The mechanism involves the transfer of momentum and energy from Earth's interior to the atmosphere at the solid-air interface. Due to the exponential decrease in atmospheric density with altitude, the velocity perturbation amplitudes of AWs significantly increase during their vertical propagation to high altitudes, favoring their detectability (Artru et al., 2001; Garcia et al., 2022).

When AWs traverse the upper atmosphere at 80–500 km, they also induce fluctuations in its ionized part—the ionosphere—which are routinely detectable using a variety of instruments (Afraimovich et al., 2001; Maruyama et al., 2016). Today, a primary method for detecting AWs in the ionosphere involves measurements of total electron content (TEC) derived from Global Navigation Satellite System (GNSS) signals (Afraimovich et al., 2013; Calais & Minster, 1998; J. Heki, 2024). TEC provides information about the total electron density

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integrated along the line of sight from a GNSS satellite to a receiver at ground, and is sensitive to plasma fluctuations driven by AWs. Compared to other techniques for observing AWs, GNSS signal measurements are routinely collected globally, particularly in seismically-active regions. They also typically provide a high temporal resolution of 1–30 s, sufficient for the analysis of short-period coseismic AW signals of several minutes.

Recent studies have demonstrated that coseismic AW signals in TEC are highly sensitive to various earthquake source parameters, such as focal mechanisms, moment magnitude (M_w), focal depth, and rupture propagation direction (Astafyeva & Heki, 2009; Astafyeva et al., 2013; Bagiya et al., 2023; Cahyadi & Heki, 2014; Catherine et al., 2017; Inchin et al., 2020; X. Meng et al., 2022). Beyond observational studies, model-guided analyses suggested that earthquake source parameters significantly influence amplitudes of AWs reaching the upper atmosphere, their AW spatial distribution, wavelengths, and propagation speeds, further highlighting the potential of GNSS-TEC observations for inferring earthquake source information (Inchin et al., 2021; Li et al., 2025; Nozuka et al., 2024). TEC observations are expected to be particularly useful in studying undersea earthquakes when seismic and geodetic observations are limited in inferring rupture evolution, and thus be used to reveal their tsunami potential.

At the same time, the sensitivity, level of uncertainty and limitations of GNSS TEC signals for quantifying coseismic AWs remain poorly understood. One of the main challenges lies in the nonlinear effects on AWs propagating upward, which result in the formation of acoustic shocks (hereafter, shocks) and their subsequent evolution into acoustic shock N-waves (hereafter, N-waves), which may propagate linearly but retain the evidence of prior nonlinear evolution (e.g., de Groot-Hedlin, 2012; Sabatini et al., 2019). This also contributes to the non-uniqueness of the inverse problem in inferring AW source characteristics, as waves tend to evolve toward similar (i.e., N-wave) forms. Consequently, coseismic AWs in the thermosphere do not directly reflect the characteristics of surface displacements driven by earthquakes, but rather the whole history of nonlinearly-evolving AWs propagating from the ground to the upper atmosphere (Nozuka et al., 2024). Thus, metrics for analyzing AW signals may include the amplitudes of the leading and trailing shocks of N-wave, signal arrival time (affected not only by the time of AW generation at the surface, but also by their nonlinear evolution and amplitudes), pulse duration and its shape. The attempt to analyze these metrics was recently performed for data/model-guided case study of the 2016 Kaikoura earthquake by Inchin et al. (2024). However, to date, the understanding of coseismic AW characteristic variability in the upper atmosphere from different earthquakes has been addressed only through data-guided statistical analyses (Bravo et al., 2022; Perevalova et al., 2014; Sunil et al., 2021), without sufficient modeling efforts to support the findings.

To better understand the advantages and limitations of using AW signals in the upper atmosphere for earthquake source quantification, Nozuka et al. (2024) explored the relationships between various source parameters and AW dynamics using coupled earthquake-atmosphere numerical simulations. The study revealed a marked and, importantly, quantifiable difference in AW signals reaching 150–250 km altitudes, resulting from earthquakes with various magnitudes, rupture propagation directions, fault stress drops and faulting mechanisms. It suggested that the radiated energy (E_R) of an earthquake is a key parameter controlling AW amplitudes. Additionally, the findings indicated that earthquakes with an M_w of 6.0 produce detectable TEC perturbations, a result that was also supported by their analysis of TEC observations during the 2023 M_w 6.2 Suzu (Japan) earthquake. However, due to the high computational cost of these simulations, which required developing dynamic earthquake models and running a comprehensive set of seismic wave propagation simulations to achieve the desired source parameters, as well as high-resolution atmospheric simulations (50–100 m), Nozuka et al. (2024) considered only seven earthquake scenarios, focusing on thrust and strike-slip subshear earthquakes of various magnitude and stress drop.

Building on the study of Nozuka et al. (2024), which demonstrated how a subset of earthquake source parameters influence upper-atmospheric AW signals using coupled earthquake-atmosphere simulations, the present study advances the field in several important ways. While Nozuka et al. (2024) focused primarily on thrust and strike-slip subshear ruptures, here we investigate a broader and more diverse set of rupture processes that have not been parametrically and systematically explored. Specifically, we examine supershear ruptures, heterogeneous ruptures, normal-faulting earthquakes, and tsunami earthquakes, each introducing distinct physical mechanisms that may markedly affect the generation and evolution of AWs in the atmosphere. By extending the parameter space in this way, our study provides new insights into earthquake-atmosphere interactions and highlights diagnostic features of AW signals that were not addressed before.

The manuscript is organized as follows. Section 2 outlines the modeling approach, including the assumptions, models and earthquake source configurations. Section 3 presents the simulation results and their analysis. Section 4 discusses the findings, while Section 5 summarizes the study and suggests future research directions.

2. Methodology

We develop multiple earthquake source models, including a thrust fault with a dip angle of 30° (Figure 1a), a normal fault with a dip angle of 60° (Figure 1b), and a pure strike-slip fault with a dip angle of 90° (Figure 1c). Instead of using simpler kinematic rupture approaches, these earthquake models are constructed through dynamic rupture simulations. This approach is selected to account for the dynamic interactions between the propagating rupture and the Earth's free surface, which are essential for realistic modeling of near-field ground motions (Kaneko & Goto, 2022), and to address the relation between earthquake scaled energy and the characteristics of the resulting AWs (Nozuka et al., 2024).

For the dynamic rupture models, we assume a planar, rectangular fault embedded in a three-dimensional homogeneous elastic medium. Unless noted otherwise, the wave speed is set as 5.7 km/s for P-waves and 3.3 km/s for S-waves (hereafter, typical earthquake scenarios). Normal (σ) and initial shear stresses (τ) increase linearly with depth while remaining uniform along the strike, as follows:

$$\sigma = \rho g z(1 - \lambda) = 7.0z \text{ (MPa, typical earthquake)} \quad (1)$$

$$\sigma = \rho g z(1 - \lambda) = 2.0z \text{ (MPa, tsunami earthquake)} \quad (2)$$

$$\tau = 0.55\sigma \text{ (MPa, typical earthquake)} \quad (3)$$

$$\tau = 0.20\sigma \text{ (MPa, tsunami earthquake)} \quad (4)$$

where g is gravitational acceleration, z is the distance along the dip in km, and the density (ρ) is 2,700 kg/m³ for typical earthquakes except tsunami earthquake with $\rho = 2,000$ kg/m³. The fluid pressure ratio (λ) is set to 0.74 for typical earthquakes (Harris et al., 2018), and to 0.90 to simulate an over-pressured fault characteristic in the tsunami earthquake scenario. Frictional resistance on the fault is modeled using a linear slip-weakening law (Ida, 1972; Palmer & Rice, 1973), where the friction coefficient (μ) is given by:

$$\mu = \mu_s + (\mu_d - \mu_s) \min(D/D_c, 1) \quad (5)$$

where μ_s and μ_d represent the static and dynamic frictional coefficients, D is the local fault slip, and D_c is a characteristic slip distance. Rupture initiation occurs within a localized nucleation patch (dashed black circles in Figures 1a and 1b), followed by spontaneous propagation beyond the nucleation patch, as detailed in the benchmark problem TPV22 (Harris et al., 2018). In this study, all seismic sources are modeled as bilateral ruptures with slip initiating at the fault center, except for the strike-slip scenarios, which exhibit dominantly unilateral rupture propagation.

To develop desired earthquake source scenarios, parameters such as fault size, dynamic friction coefficient (μ_d), static friction coefficient (μ_s), and characteristic slip (D_c) are varied, with 1–100 simulations conducted to obtain the target moment magnitude and static stress drop (Table 1). Notably, a large number (100) of simulations are performed to construct the tsunami earthquake scenario due to the narrow parameter range necessary to match the source characteristics reported in observational studies (see Section 3.4 for details). Stress drop of an earthquake $\Delta\sigma_E$ is calculated using shear stress values before and after the earthquake at each fault grid node, weighted by the final slip (Noda et al., 2013; Nozuka et al., 2024). We also report radiated energy, E_R , of each source model, calculated as

$$E_R = \int_{\Sigma} \frac{\tau^o(\xi) + \tau^f(\xi)}{2} S(\xi) d\Sigma - \int_0^\infty \int_{\Sigma} \tau(\xi, t) V(\xi, t) d\Sigma dt, \quad (6)$$

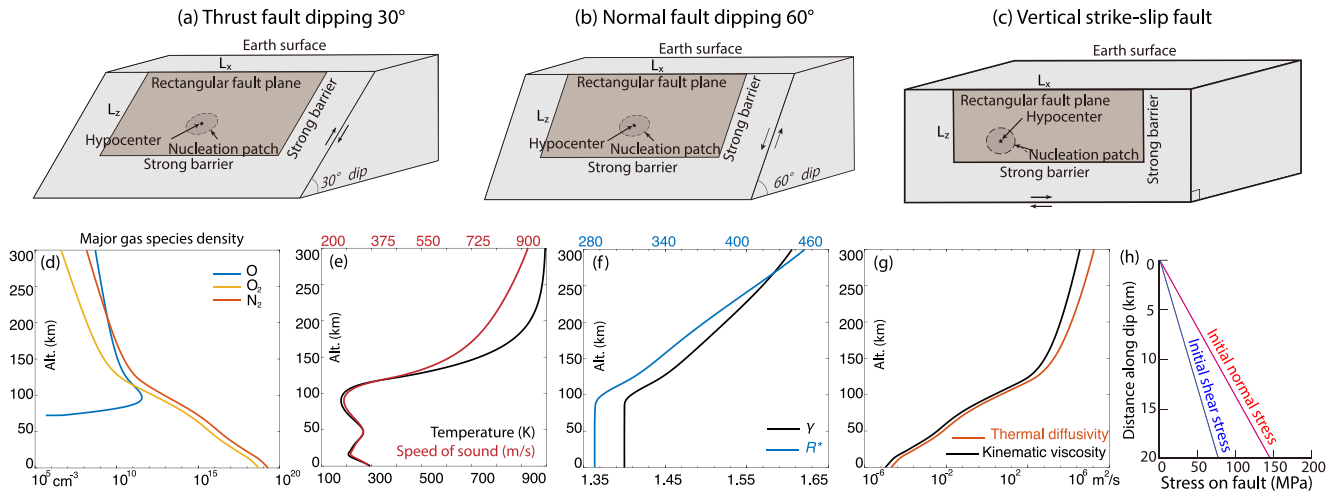


Figure 1. (a–c) Schematics of the earthquake dynamic rupture model for each fault mechanism. Vertical profiles of (d) major atmospheric species densities, (e) temperature and speed of sound, (f) adiabatic index (γ) and specific gas constant R^* , and (g) momentum and thermal diffusivities. (h) The depth-dependence of shear stress and normal stress on the fault.

where τ is the shear stress on the fault, τ^0 and τ^f are the initial and final shear stresses, respectively, S and V are the slip and slip rate at a point ξ on the fault, respectively, and Σ is the source area (Kaneko & Shearer, 2014; Kostrov, 1974).

At the bottom boundary of MAGIC model (Snively, 2013; Snively & Pasko, 2008), which represents a seismic-acoustic coupling interface, we use vertical surface velocities from SPEC-FEM3D dynamic rupture simulations (Kaneko et al., 2008; Komatitsch & Tromp, 1999) to serve as the bottom boundary condition. MAGIC solves the compressible, nonlinear Navier–Stokes equations to simulate AW generation and propagation (Inchin et al., 2020, 2021). The equations for mass, momentum, and energy conservation solved in MAGIC are given by:

$$\begin{cases} \frac{\partial \rho_a}{\partial t} + \nabla \cdot (\rho_a \mathbf{v}) = 0 \\ \frac{\partial \rho_a \mathbf{v}}{\partial t} + \nabla \cdot (\rho_a \mathbf{v} \mathbf{v} + P \mathbf{I}) = \rho_a \mathbf{g} + \nabla \cdot \boldsymbol{\tau}_v \\ \frac{\partial E}{\partial t} + \nabla \cdot ((E + P) \mathbf{v}) = \rho_a \mathbf{g} \cdot \mathbf{v} + (\nabla \cdot \boldsymbol{\tau}_v) \cdot \mathbf{v} + k \nabla^2 T \end{cases} \quad (7)$$

where ρ_a is the atmospheric density, $\mathbf{v}$ is the velocity vector, P is the atmospheric pressure, $\mathbf{g}$ is the gravitational acceleration, E is the total energy, T is the temperature, $\boldsymbol{\tau}_v$ is the viscous stress tensor, k is the thermal

Table 1
Earthquake Source Parameter Ranges Considered in This Study

Sim #	Fault size ($L_x \times L_y$)	$\mu_s/\mu_d/\mu_0$	D_c	Total number of simulations
1	100 × 15	0.57/0.50/0.55	0.3 m	1
2	100 × 15	0.59/0.478–0.51/0.55	0.3 m	5
3	20 × 10	0.65–0.75/0.42–0.45/0.55	0.3 m	7
4	–	–/–/–	–	–
5	20 × 10–28 × 14	0.556–0.69/0.455(±0.4)–0.55(±0.4)/0.55	0.3 m	24
6	20 × 10–32 × 16	0.565–0.74/0.45(±0.6)–0.55(±0.6)/0.55	0.3 m	27
7	20 × 10–64 × 15	0.101–0.70/0.06–0.52/0.1–0.55	0.3–7.2 m	100
8	–	–/–/–	–	–

Note. Parameters for Sim #4 and Sim #8 are not listed, as they are provided in Nozuka et al. (2024).

Table 2
Earthquake Source Parameters in Each Model

Sim #	Fault type/EQ type	Fault size in km ($L_x \times L_y$)/ V_s/V_p	$\mu_s/\mu_d/D_c$	Resulting M_w /Stress drop
1	Strike/subshear	$100 \times 15/3.3/5.7$ km/s	0.59/0.50/0.3 m	7.1/2.8 MPa
2	Strike/supershear	$100 \times 15/3.3/5.7$ km/s	0.57/0.50/0.3 m	7.1/2.8 MPa
3	Normal/typical	$20 \times 10/3.3/5.7$ km/s	0.68/0.44/0.3 m	6.5/4.4 MPa
4	Thrust (Nozuka et al., 2024)/typical	$20 \times 10/3.3/5.7$ km/s	0.75/0.45/0.3 m	6.5/4.3 MPa
5	Thrust/hetero rupture	$24 \times 12/3.3/5.7$ km/s	$0.565/0.51 \pm 0.2/0.3$ m	6.5/4.4 MPa
6	Thrust/hetero rupture	$20 \times 10/3.3/5.7$ km/s	$0.714/0.45 \pm 0.3/0.3$ m	6.5/4.3 MPa
7	Thrust/tsunami	$53 \times 15/1.6/2.8$ km/s	0.2003/0.14/2.9 m	6.5/0.6 MPa
8	Thrust (Nozuka et al., 2024)/typical	$29 \times 14.5/3.3/5.7$ km/s	0.55/0.53/0.3 m	6.5/1.2 MPa

conductivity, and $\mathbf{I}$ is the identity tensor. Further details on MAGIC's system of equations and underlying assumptions are provided in Appendix A1 of Zettergren and Snively (2015).

Atmospheric vertical profiles of temperature and the major atmospheric gas densities of O, O₂, and N₂ used in MAGIC are derived from the NRLMSISE00 model (Picone et al., 2002) and are illustrated in Figures 1d and 1e. These profiles, derived for 35°N/120°E at 12 p.m. local time on 28 June 2020, are used to compute the adiabatic index, specific gas constant, and thermal and momentum diffusivity (Figures 1f and 1g). These profiles represent atmospheric conditions during a calm geomagnetic period at mid-latitudes. Temporal variations in the atmospheric state are omitted, as they are expected to have minimal impact on the 10-min wave propagation within selected numerical domains. Additionally, to avoid complications in the analysis of AW dynamics, horizontal winds are excluded from the simulations. The MAGIC simulations below ~150 km use a 100-m horizontal and 50-m vertical resolution grid, with ~200 m uniform resolution at altitudes of ~200 km and above (sufficient to resolve the AWs at these altitudes). We note that these profiles and resolutions in MAGIC simulations are the same as those used by Nozuka et al. (2024), thus allowing us to directly compare the results between the two studies. The detailed workflow for simulating atmospheric AWs in the MAGIC model is provided in Text S4 in Supporting Information S1.

Since one of the most prominent observational techniques for detecting AWs in the upper atmosphere is GNSS TEC, this study focuses on the analysis of AW fluid velocities, which can serve as effective proxies for related ionospheric plasma fluctuations. Fluid velocities along the direction of geomagnetic field lines are linked to the efficient momentum transfer between neutral particles and ions/electrons, resulting in observable density perturbations in the ionospheric plasma (Zettergren & Snively, 2015). In our models, AWs are generated by vertical ground velocities. Accordingly, we focus on the vertical component of neutral fluid velocity, which provides a direct measure of upward acoustic energy propagation and facilitates comparison with the surface forcing. This choice also reduces complexity associated with horizontal motions, including sensitivity to local topography and geomagnetic geometry. We note that horizontal velocity components can influence ionospheric coupling, particularly at low latitudes where magnetic field lines are nearly horizontal. While such effects are not explicitly addressed here, vertical velocity remains a robust and general diagnostic of AW dynamics, whereas the full plasma response depends on location-specific magnetic field geometry.

3. Results

This section presents seismic wave and AW simulation results conducted for various earthquake sources, the characteristics of which are provided in Table 2. We begin by analyzing AWs generated during two types of fault ruptures for right-lateral strike-slip earthquakes of moment magnitude (M_w) 7.1: subshear rupture (Sim #1) and supershear rupture (Sim #2). Next, we present the results for two M_w 6.5 earthquakes with comparable stress drops ($\Delta\sigma_E$), but with different faulting mechanisms: normal faulting (Sim #3) and thrust faulting (Sim #4). Then, we discuss simulations of M_w 6.5 thrust earthquakes from Sim #5 and Sim #6, investigating the impact of slip distribution heterogeneity on AW characteristics in the upper atmosphere. Finally, we compare the AW dynamics generated by a tsunami earthquake and a typical thrust earthquake (Sim #7 and Sim #8). Animations illustrating seismic wave dynamics at the surface and AW propagation for each simulation are provided in Supporting Information S1.

The choice of earthquake magnitudes is guided by consistency with prior work, physical relevance, and computational constraints. We adopt M_w 6.5 for thrust, normal, heterogeneous, and tsunami earthquake scenarios to enable direct comparison with Nozuka et al. (2024), while M_w 7.1 is used for strike-slip earthquakes to represent typical supershear events observed in the M_w 7 range (e.g., Bao et al., 2019; Ye et al., 2025). Larger-magnitude simulations would require substantially larger computational domains and increased cost, which limits the range of scenarios that can be explored. We note that differences in M_w across scenarios may affect strict comparability; therefore, our analysis primarily focuses on trends within the same M_w . Earthquake parameters were selected to facilitate direct comparison with the results of Nozuka et al. (2024), while addressing first-order aspects of earthquake-atmosphere coupling.

Note that we define U and U' as vertical displacement and velocity field at the Earth's surface, respectively, derived from SPECFEM3D simulations. The variable W represents AW vertical fluid velocities in the atmosphere as simulated with MAGIC. In all simulations, the center of the numerical domain is referred to as $(X = 0, Y = 0)$, with positive and negative directions labeled as $X+$ and $Y+$, $X-$, and $Y-$, respectively, and the altitude is represented by Z . V_p and V_s denote P-wave and S-wave velocities, respectively.

3.1. Subshear Versus Supershear Strike-Slip Earthquakes

We begin our discussion with AWs generated in simulations using a right-lateral strike-slip fault model as the earthquake source. The simulations exhibit two distinct rupture propagation regimes: subshear (Sim #1, Figures 2a–2k) and supershear (Sim #2, Figures 2l–2v). Both simulations use identical fault dimensions of 15×100 km. In Sim #2, a reduced μ_s leads to the transition from subshear to supershear rupture (Figure 2m) by facilitating the nucleation of a daughter crack at the shear stress peak induced by the S-wave ahead of the primary rupture front (Andrews, 1976; Burridge, 1973). As a result, the rupture in Sim #2 propagates at 5.3 km/s ($1.6 V_s$), whereas in Sim #1 it propagates at 3.0 km/s ($0.9 V_s$), both along the Mode II direction. To mitigate the supershear transition triggered by the Earth's free surface (Kaneko & Lapusta, 2010), we apply a frictional cohesion of 1 MPa to the uppermost 3 km of the fault in both simulations.

Both simulations yield comparable static $\Delta\sigma_E = 2.8$ MPa and $M_w = 7.1$. However, the radiated energy (E_R) in Sim #2 (1.6×10^{15} J) exceeds that in Sim #1 (1.4×10^{15} J) by $\sim 14\%$. This difference is attributed to the lower static friction coefficient (μ_s) in Sim #2, which reduces fracture energy and enhances the efficiency of energy radiation. In both simulations, ruptures initiate at $X = -90$ km and a depth of 10 km, producing similar slip distributions (Figures 2d, 2h, 2o, and 2s). In Sim #2, the rupture speed exceeds V_s , and distinct Mach waves are visible in the U' field (Figure 2t). The amplitudes of the leading waves in the U' field in Sim #2 are about three times larger (3.4 mm/s, Figure 2t) than those in Sim #1 (1.2 mm/s, Figure 2i), due to the P-wave directivity effect as the rupture velocity approaches $0.9V_p$. Mach waves in the supershear case exhibit reduced attenuation, resulting in notable positive-phase U' propagating in the $X+$ and $Y+$ directions (Figure 2j). Vertical velocity peaks at 0.57 m/s in Sim #2 and 0.21 m/s in Sim #1, with Sim #2 producing more than twice the local U' . Beyond the vicinity of the fault, U' amplitudes remain higher in Sim #2 (Figure 2v).

Figure 3 shows the results of MAGIC simulations with AW sources in the aforementioned subshear and supershear earthquake scenarios. AWs are generated over the ruptured areas and off-faults (in the case of the supershear scenario, dominantly due to Mach wave propagation). At 80 km altitude, the morphology of AWs differs markedly between the two simulations across the entire numerical domain (Figures 3a and 3h). First, the differences arise from earlier arrivals of AWs (~ 12 s) in the supershear case, reflecting their earlier excitation times (Figures 2i and 2t). Second, Sim #2 produces much larger AW vertical velocities W reaching 8.0 m/s, in comparison to 4.9 m/s ($\sim 40\%$) in Sim #1 (Figures 3f and 3m). We note that at 80 km altitude AWs still propagate in a fairly linear regime, and thus peak absolute W are very similar on both sides of the rupture, that is, in the $Y+$ and $Y-$ directions.

At 200 km altitude (the rough altitude of GNSS TEC signals resulting from AWs), where separate shocks (evolved from AWs) merge into nearly uniform shock N-waves, the spatial differences in wavefields become less pronounced (Figures 3c and 3j). Yet, the amplitudes differ significantly, peaking at 115 and 138 m/s in Sim #1 and Sim #2, respectively ($\sim 17\%$ difference, Figures 3g and 3n). Similar differences in AWs are visible at higher altitudes. For example, at 250 km they peak at 93.6 and 115 m/s in Sim #1 and Sim #2, respectively ($\sim 20\%$ difference). The difference in signal periods also becomes more pronounced, with larger N-wave elongation in

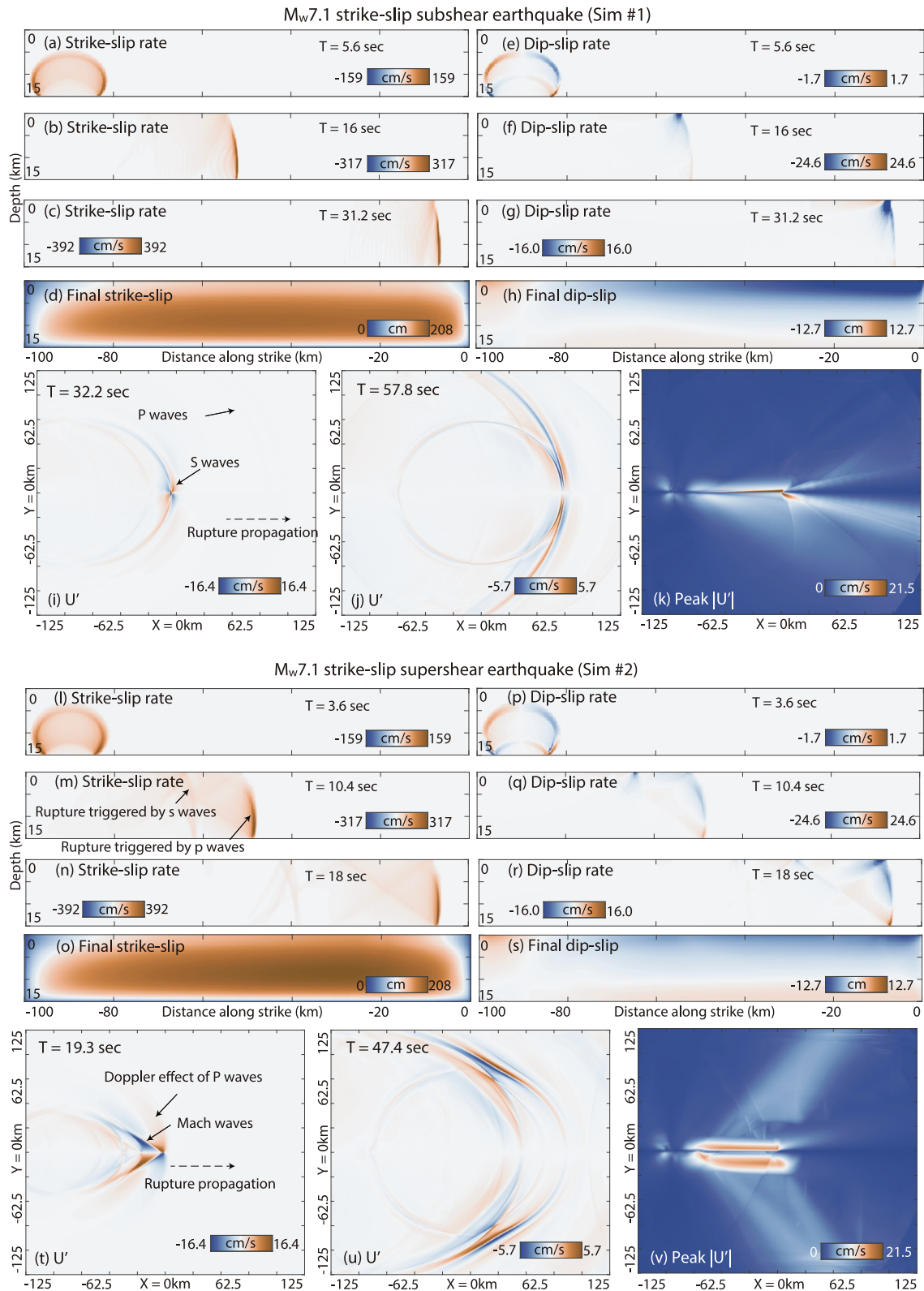


Figure 2. Rupture dynamics and associated surface ground motions for $M_w 7.1$ subshear (a–k) and supershear (l–v) strike-slip earthquake scenarios. (a–c, l–n) and (e–g, p–r) show time snapshots of the strike-slip and dip-slip slip-rate components on the fault, respectively. Panels (d, o) and (h, s) display the final distributions of strike-slip and dip-slip fault slip. (i–j, t–u) Illustrate the temporal evolution of U' at the Earth's surface, while (k, v) depict the maximum U' attained at the Earth's surface.

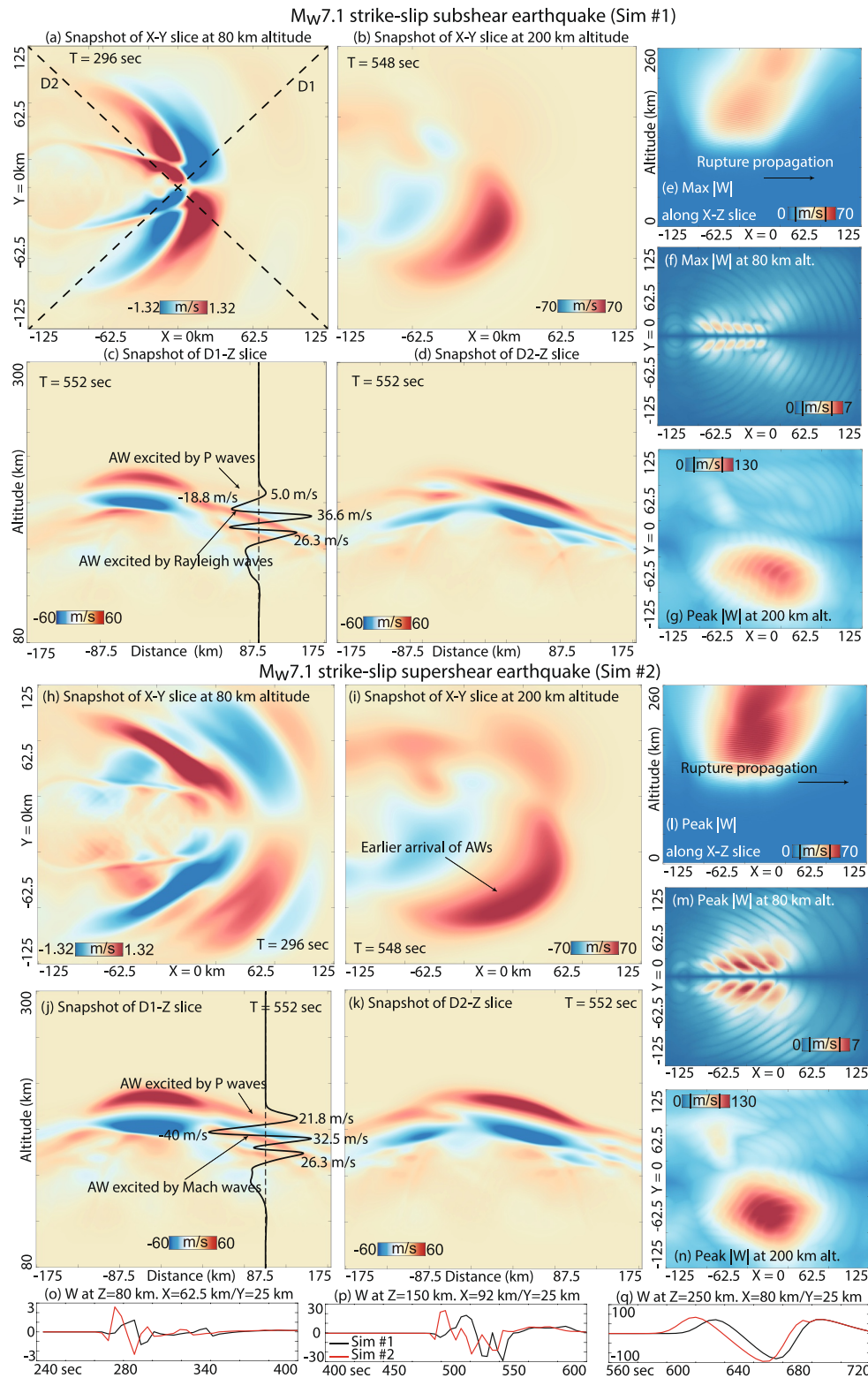


Figure 3. Acoustic waves generated in M_w 7.1 strike-slip subshear (a–g) and supershear (h–n) earthquake scenarios. (a, b) Show snapshots of W at 80 and 200 km altitude from Sim #1, while (c, d) present cross-sections of W along transects Z–D1 and Z–D2. (e–g) Display peak $|W|$ for Sim #1: (e) across X – Z slices, (f) at 80 km altitude, and (g) at 200 km altitude. (h, i) Show snapshots of W at 80 and 200 km altitude from Sim #2, and (j, k) depict W along transects Z–D1 and Z–D2. (l–n) Present peak $|W|$ for Sim #2: (l) along X – Z slices, (m) at 80 km altitude, and (n) at 200 km altitude. (o–q) Show temporal variations of W from Sim #1 and Sim #2 at three altitudes.

Sim #2 resulting from its larger shock amplitudes. The dominant periods are ~ 16 s in Sim #1 and ~ 24 s in Sim #2. The signal arrival times differ by ~ 20 s between the simulations (Figures 3b, 3i, and 3o–3q).

In contrast with nearly symmetric absolute W field at 80 km, W at 200 km does not exhibit symmetry across the rupture. Figures 3g and 3n show asymmetry in $|W|$ between the $Y+$ and $Y-$ directions, arising from differences in the evolution of AW packets into shocks on either side of the rupture and their subsequent merging into N-waves. This further demonstrates the importance of nonlinear AW propagation, and we refer to Nozuka et al. (2024) which elaborated on the asymmetry of AW wavefields in strike-slip earthquakes in detail. Interestingly, AWs generated by P waves exhibit relatively strong amplitudes in the supershear case, reaching 20 m/s at altitudes above 200 km (Figures 3c, 3d, 3j, and 3k). This highlights the potential for detecting P -wave directivity signatures in the ionosphere via TEC observations. However, these TEC signals may be obscured by the stronger AWs generated over the ruptured area and by Mach waves.

The maximum absolute amplitude of W over the entire simulation domain and duration occurs at 186 km altitude in Sim #2 (139 m/s), which is $\sim 20\%$ greater than the corresponding peak value in Sim #1 (115 m/s at 197 km altitude) (Figures 3e–3l). The regions of peak $|W|$ amplitudes shift toward the $X+$ and $Y-$ directions (Figures 3f, 3g, 3m, and 3n), reflecting the combined influence of rupture propagation direction (toward $X+$) and the polarity of ground vertical velocities U' . This asymmetry of the AW wavefield toward the rupture propagation direction is more pronounced in the supershear case than in the subshear case, highlighting the enhanced directionality effect of energy radiation associated with the supershear rupture dynamics (Figures 3e and 3l).

To summarize, simulations incorporating subshear and supershear earthquake scenarios with comparable moment magnitudes and stress drops demonstrate notably different AW characteristics reaching the upper atmosphere. Differences reach tens of percent in amplitude and more than 12–16 s in arrival times, as well as in the periods of the generated N-waves.

3.2. Normal Versus Thrust Faulting

Here, we examine simulation results for M_w 6.5 normal (Sim #3) and thrust (Sim #4) faulting earthquake scenarios. Figure 4 illustrates the key features of SPECFEM3D simulations. In Sim #3, the fault dip angle is set to 60° , whereas all thrust-fault cases of this study, including Sim #4 (adapted from Nozuka et al. (2024)), assume a 30° dip angle, in accordance with Anderson's theory of faulting (Anderson, 1905). The direction of initial shear traction differs between Sim #3 and Sim #4 due to their respective faulting mechanisms. In both cases, rupture nucleation occurs at the center of the fault at the depth of 7 km along the dip direction (Figures 4a and 4d). The ruptures primarily propagate upward toward the surface before spreading bilaterally along the strike direction (Figures 4b and 4e). The final slip amplitudes are comparable between the two scenarios, reaching 1.7 m in Sim #3 and 1.8 m in Sim #4 along the dip direction (Figures 4c and 4f), resulting in equivalent M_w . Fault dimensions and static stress drops are also similar in both cases (see Table 2).

As expected from their faulting mechanisms, Sim #3 produces dominant downward motion at the surface, whereas Sim #4 produces dominant upward motion (Figures 4g, 4i, 4j, and 4l). The maximum absolute values of U' are 0.8 m/s for Sim #3 and 0.5 m/s for Sim #4. Furthermore, U' are spatially more distributed in Sim #4, while in Sim #3 they are concentrated near the fault trace (Figures 4h and 4k). This localized distribution in the normal-faulting case is attributed to the steeper dip angle, which confines vertical motion to a narrower region.

The contrasting faulting mechanisms in Sim #3 (normal) and Sim #4 (thrust) lead to very distinct characteristics in the resulting AWs propagating into the upper atmosphere (Figure 5). In Sim #3, the initial surface motion is dominated by subsidence, producing AWs with negative leading phases of dominant amplitude in the lower atmosphere (Figure 5a). Conversely, Sim #4 primarily generates uplift at the surface, resulting in AWs with positive leading phases of dominant amplitude in the lower atmosphere (Figure 5b). Despite these differences at low altitudes, the AWs from both scenarios evolve into shocks and eventually into N-waves (Figures 5b and 5h), though with their markedly different characteristics in the upper atmosphere.

At 200 km altitude, the spatial distribution of $|W|$ differs notably between the two scenarios: Sim #3 exhibits peak $|W|$ values concentrated in the $Y-$ direction, whereas Sim #4 shows peak values oriented toward the $Y+$ direction (Figures 5c, 5f, 5i, and 5l). This directional asymmetry arises from the dominant subsidence-induced ground motion in Sim #3, which drives seismic wave propagation preferentially toward $Y-$, and the uplift-induced motion in Sim #4, which promotes propagation toward $Y+$ (Figures 5f and 5l). The maximum $|W|$ over the

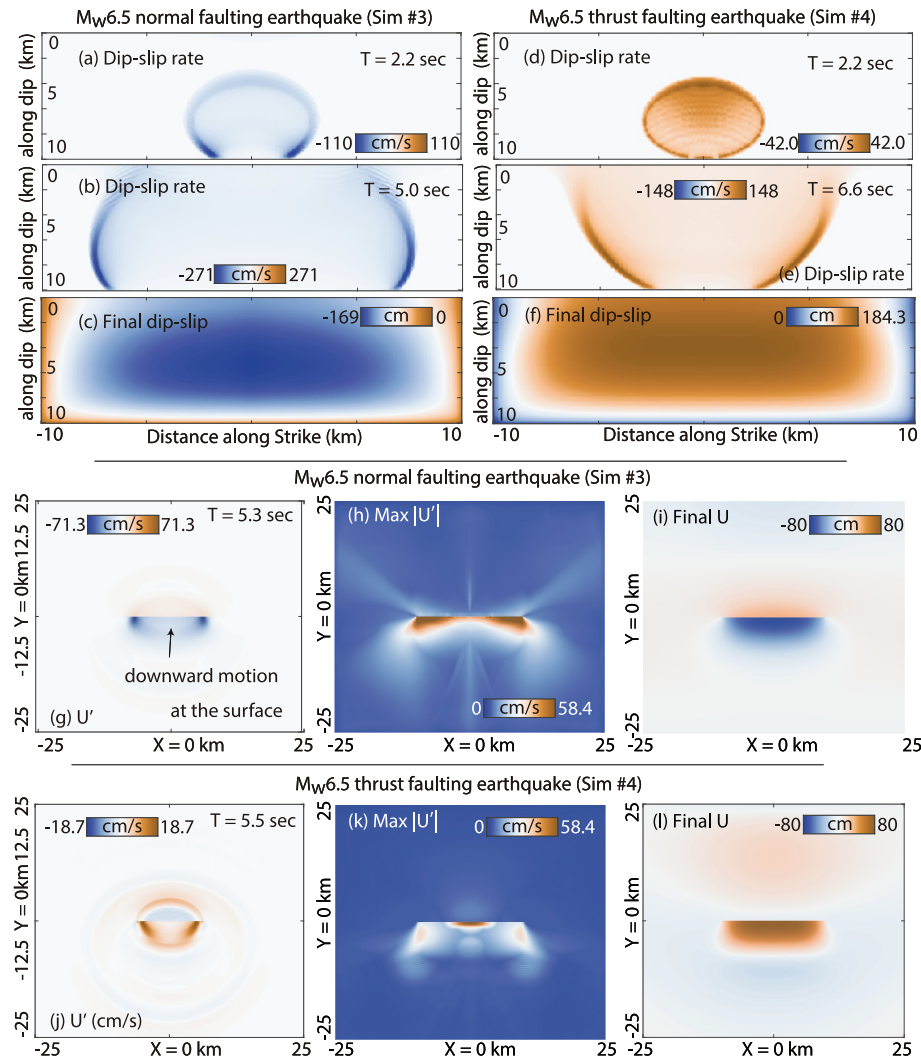


Figure 4. Earthquake rupture dynamics and associated surface ground motions for M_w 6.5 normal (Sim #3) and thrust (Sim #4) faulting scenarios. (a, b) Show snapshots of dip-slip rates on the fault for Sim #3, with the final dip-slip distribution shown in (c). (d, e) Show snapshots of dip-slip rates on the fault for Sim #4, with the final dip-slip distribution shown in (f). (g, j) Present snapshots of vertical surface velocity fields (U'), (h, k) show peak U' , and (i, l) display final displacements U for Sim #3 and Sim #4, respectively.

entire simulation domain and duration occurs at an altitude of 142 km in Sim #3 (52.6 m/s), which is less than half of the peak value in Sim #4 (114 m/s at 153 km altitude) (Figures 5c and 5i). Due to their larger amplitudes in Sim #4, we find earlier arrival of AWs at thermospheric altitudes by 4–8 s (Figures 5b and 5h, also Figure 6). These results suggest that while opposite polarities of seismic waves generate differently polarized AWs in the lower atmosphere, they become indistinguishable in the thermosphere due to their nonlinear evolution and steepening, and the formation of N-waves.

Figures 6a and 6b show time series of normalized vertical velocity (W , scaled by peak signal amplitude) across various altitudes at the locations $X = 0/Y = -6.4$ km and $X = 0/Y = 6.4$ km from Sim #3 and Sim #4, respectively. Additionally, Figures 6c–6e show spatial distributions of W at $X = 0/Y = 0$ location at three moments of time. Below the thermosphere (0–90 km), AWs exhibit a negative leading phase for the normal-fault earthquake and a positive leading phase for the thrust earthquake. The amplitudes of positive and negative AW phases differ due to shock formation and superposition of AWs from different rupture zones. Reaching the lower thermosphere, the initially negative leading phases in Sim #3 evolve into a set of individual shocks, eventually merge into a distinct N-wave pulse by 150 km. This apparent phase reversal results from nonlinear AW evolution, where leading negative shocks merge with trailing positive shocks (due to differences in shock propagation

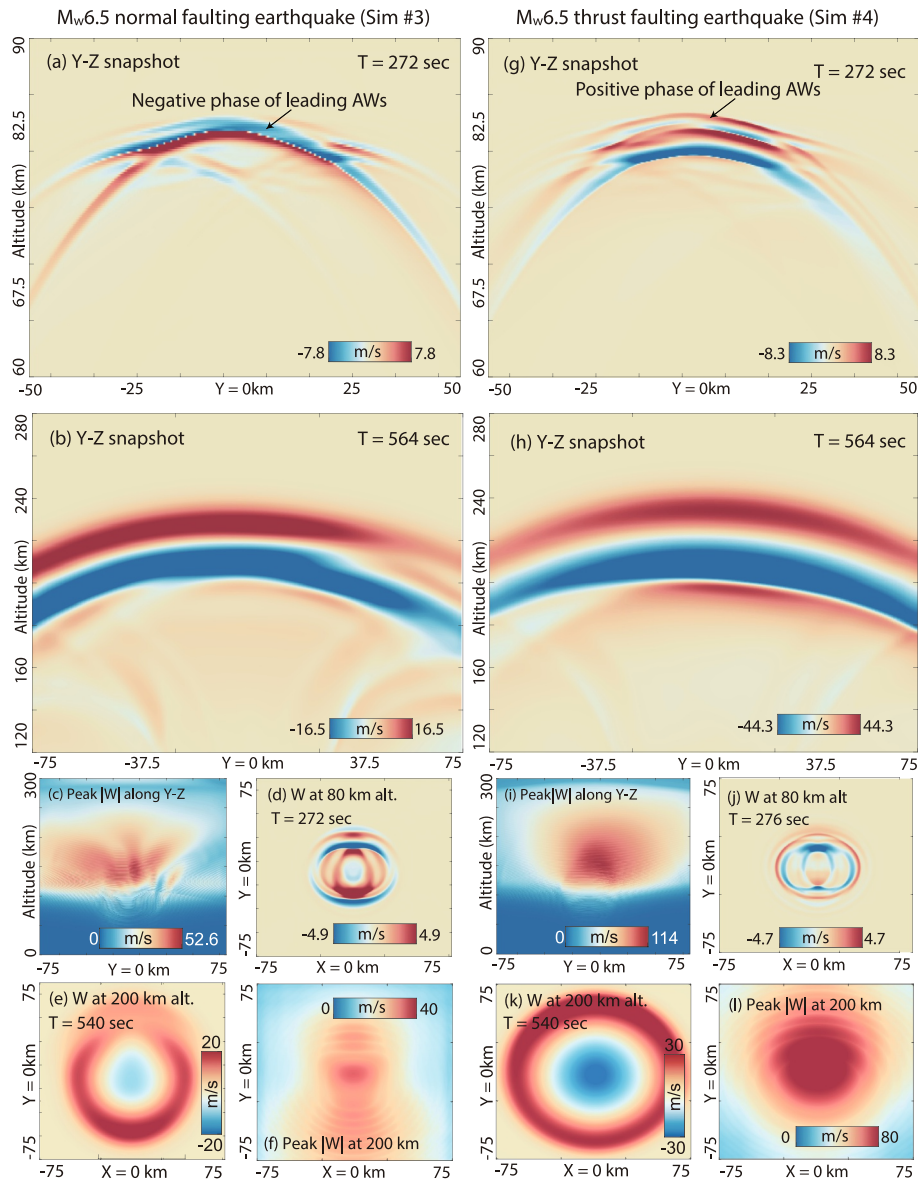


Figure 5. Acoustic waves generated by M_w 6.5 (a–f) normal and (g–l) thrust faulting scenarios. (a, b) Show snapshots of vertical fluid velocity (W) along the Y – Z transect for the normal faulting case, with the maximum absolute vertical velocity ($|W|$) shown in (c). (d–f) Display snapshots of W : (d) at 80 km altitude, (e) at 200 km altitude, and (f) the corresponding $|W|$ at 200 km altitude. (g, h) Present snapshots of W along the Y – Z transect for the thrust faulting case, with the maximum $|W|$ shown in (i). (j, k) Show W : (j) at 80 km altitude, (k) at 200 km altitude, and (l) the corresponding $|W|$ at 200 km altitude.

speed), reducing resulting N-wave amplitudes. In contrast, leading positive phase of AWs for thrust earthquake in Sim #4 persists without merging with trailing negative phases, eventually evolving into an N-wave (Figure 6b).

3.3. Effects of Slip and Rupture Heterogeneities on Resulting AWs

In this section, we examine the effects of fault slip and rupture heterogeneity on AW generation and propagation. We use two earthquake models with different spatial distributions of dynamic friction coefficient (μ_d). We use von Karman autocorrelation functions (ACF), which are commonly employed to model heterogeneous slip distributions of large earthquakes, to mimic spatial variability over the fault (Mai & Beroza, 2002). Since dynamic rupture modeling does not allow direct prescription of final slip distributions, we vary the ACF correlation lengths and the range of μ_d values to construct different rupture scenarios while preserving equivalent moment

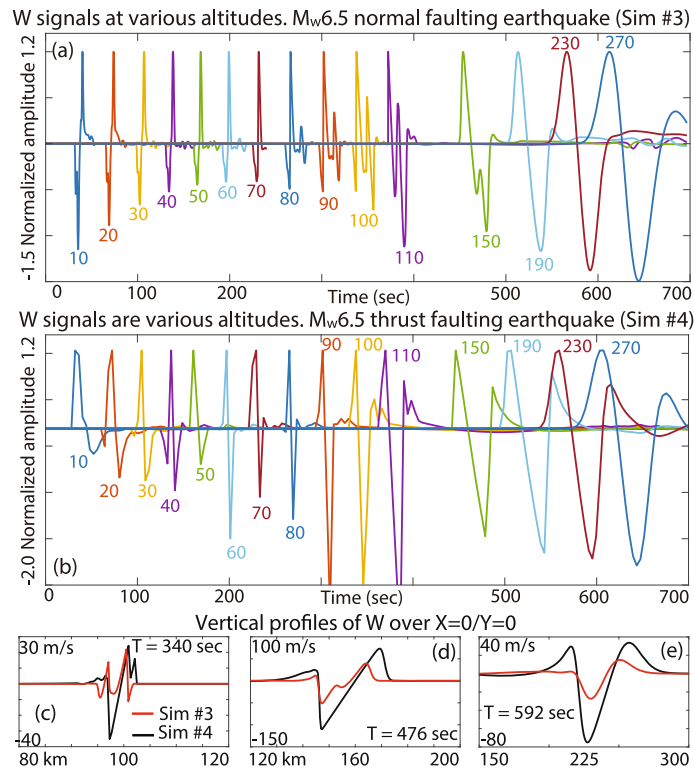


Figure 6. Normalized W at various altitudes (specified with numbers near each time series with the same color) over $X = 0/Y = -6.4$ km and $X = 0/Y = 6.4$ km locations for (a) Sim #3 and (b) Sim #4, respectively. The number near each signal identifies the altitude. (c–e) Show snapshots of the 1D profiles of W at $X = 0, Y = 0$ for Sim #3 and Sim #4 at three time steps. The red solid line represents acoustic waves (AWs) from Sim #3, and the black solid line represents AWs from Sim #4.

magnitudes. As a result, in Sim #5 we assume horizontal and vertical correlation lengths as 4.8 and 5.7 km, respectively, with μ_d ranging from 0.31 to 0.71 (Figure 7a). In contrast, Sim #6 features significantly shorter horizontal and vertical correlation lengths of 0.8 and 0.6 km, respectively, with μ_d varying between 0.15 and 0.75 (Figure 7b). Thus, Sim #6 exhibits greater heterogeneity in both rupture dynamics and final slip distribution compared to Sim #5 (Figures 7b–7d and 7i–7k).

The increased complexity of μ_d in Sim #6 results in a rupture duration of 11 s, in comparison to 6 s in Sim #5, despite other source parameters being comparable between the simulations. The static stress drops ($\Delta\sigma_E$) are similar, constituting 4.4 MPa for Sim #5 and 4.3 MPa for Sim #6. These scenarios yield a moment magnitude of $M_w = 6.5$, consistent with Sim #4 with a uniform μ_d . The maximum fault slip values are also similar across three cases: 1.8 m for Sim #4, 2.1 m for Sim #5, and 1.9 m for Sim #6 (Figures 4f, 7d, and 7k). In Sim #5, the slip distribution is concentrated in the $X-$ direction, as elevated μ_d values in the $X+$ direction inhibit rupture propagation (Figure 7d).

The snapshots of (U') from Sim #5 and Sim #6 (Figures 7e and 7l) reveal asymmetric and spatially heterogeneous ground motion patterns, in contrast to a more symmetric distribution observed in the homogeneous case (Sim #4; Figure 4i). The maximum values of U' are 0.5, 0.8, and 1.0 m/s for Sim #4, Sim #5, and Sim #6, respectively. In both heterogeneous rupture scenarios, seismic wave propagation is enhanced in the $X-$ direction, consistent with the spatial concentration of the slip and the inhibition of rupture growth in the $X+$ direction (Figures 7f and 7m).

Figures 8a–8j show the snapshots of (W) along the $Y-Z$ plane and over the center of the numerical domain, as well as horizontal slices at 80 and 200 km altitudes from Sim #5 and Sim #6. Sim #5 produces maximum $|W|$ of 124 m/s at 200 km altitude, while in Sim #6, $|W|$ peaks at 114 m/s at 153 km altitude. These values are comparable to the maximum $|W|$ observed in Sim #4 (114 m/s at 153 km), varying by only $\sim 8\%$. At the same time, the peak $|W|$ values are slightly shifted toward the $X-$ direction in Sim #5 and Sim #6, compared to Sim #4 (Figures 8e–8j), reflecting the influence of rupture propagation direction. This indicates that large-scale rupture processes (on the

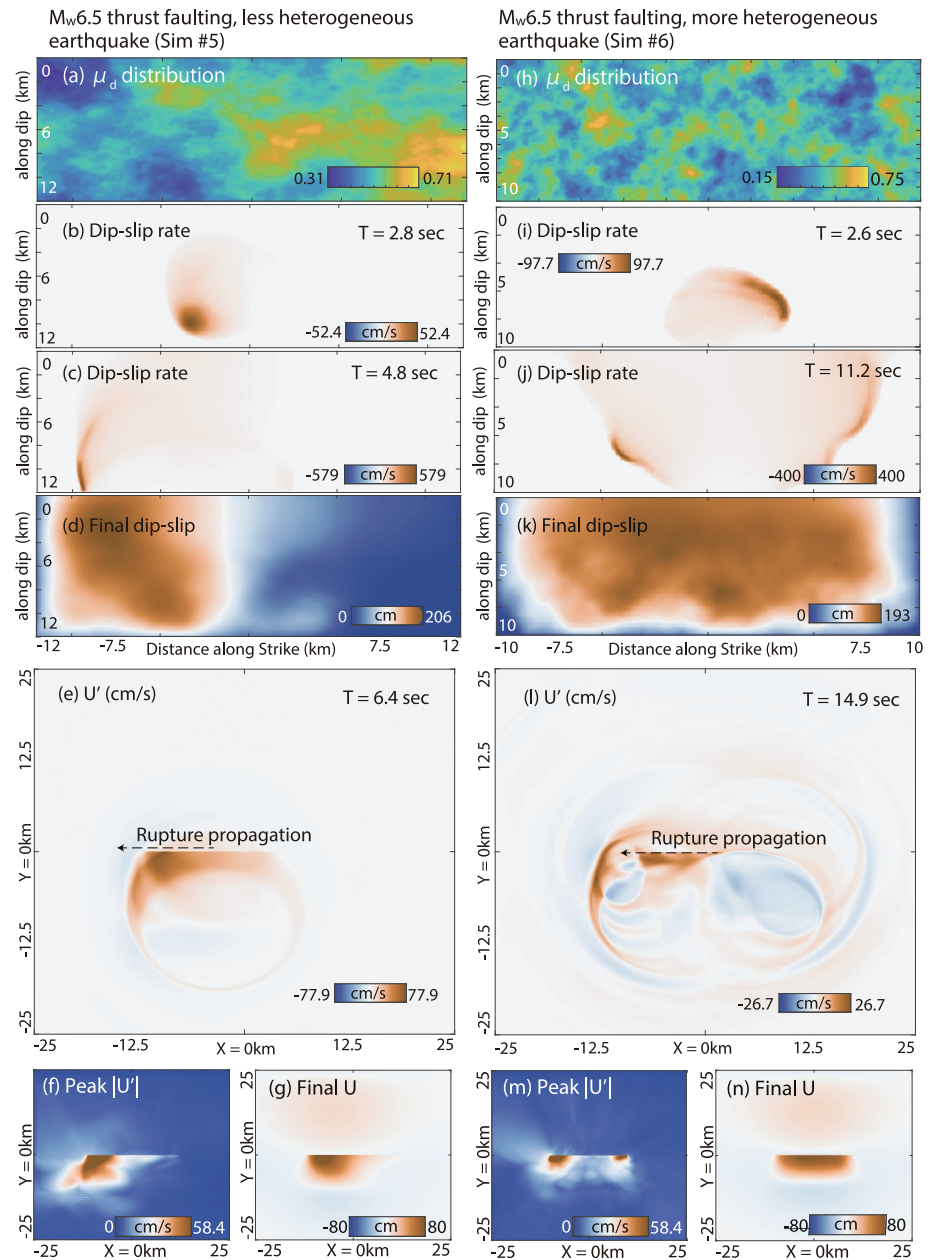


Figure 7. Earthquake rupture dynamics and associated surface ground motions for M_w 6.5 thrust faulting with (a–g) less heterogeneous (Sim #5) and (h–n) more heterogeneous (Sim #6) rupture scenarios. (a) Shows the spatial distribution of the dynamic friction coefficient (μ_d) on the fault for Sim #5. (b, c) Present time snapshots of dip-slip rates, with the final dip-slip distribution shown in (d). (e) Illustrates the evolution of vertical surface velocity fields (U'), while (f–g) show peak $|U'|$ and the final vertical surface displacement (U), respectively, for Sim #5. Similarly, (h) shows the distribution of μ_d for the more heterogeneous case (Sim #6). (i, j) Present time snapshots of dip-slip rates, with the final distribution shown in (k). (l) Displays the evolution of U' , and (m, n) show peak $|U'|$ and the final surface displacement (U) for Sim #6.

order of ~ 10 km) can influence the spatial distribution of AWs at altitudes of 150 km. At 250 km altitude (see Supporting Information S1), the maximum $|W|$ values are 76.5 and 66.2 m/s for Sim #5 and Sim #6, respectively ($\sim 14\%$ difference).

As AWs propagate upward and evolve into N-waves, analyzing individual shocks from AWs formed over various parts of rupture becomes less feasible (Figures 8b, 8d, 8g, and 8i). In contrast, in the lower atmosphere, for example, at ~ 80 km where AWs have not yet evolved into N-waves, the influence of rupture heterogeneity on

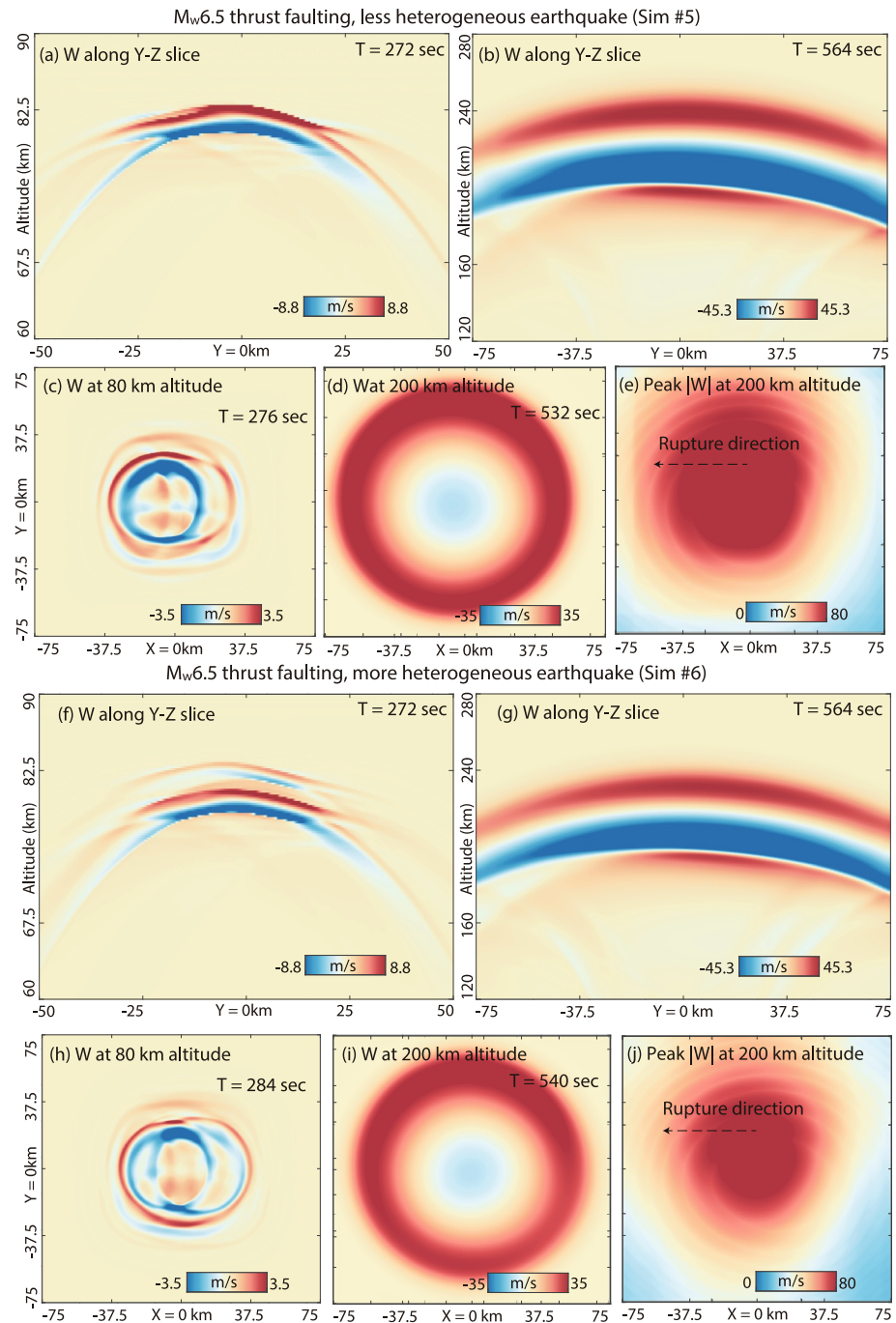


Figure 8. Acoustic waves generated by an M_w 6.5 thrust faulting event with (a–e) less heterogeneous (Sim #5) and (f–j) more heterogeneous (Sim #6) rupture scenarios. (a, b) Show snapshots of vertical fluid velocity (W) along the Y – Z transect for Sim #5. (c–e) Show W : (c) at 80 km altitude, (d) at 200 km altitude, and (e) the corresponding peak $|W|$ at 200 km altitude for Sim #5. (f, g) Show snapshots of vertical fluid velocity (W) along the Y – Z transect for Sim #6. (h–j) Show W : (h) at 80 km altitude, (i) at 200 km altitude, and (j) the corresponding peak $|W|$ at 200 km altitude for Sim #6.

AW waveform shapes is more pronounced (Figures 8a, 8c, 8f, and 8h). This suggests that small-scale rupture and slip heterogeneities (of $\lesssim 10$ km) are inherited by AWs propagating in the lower atmosphere, while they are likely indistinguishable in the thermosphere. We note that N-waves formed in the lower-thermosphere still inherit the full history of nonlinear AW evolution accumulated over the entire range of altitudes.

3.4. Tsunami Earthquakes Versus Typical Thrust Earthquakes

In this section, we construct a scenario (Sim #7) that satisfies the characteristics of tsunami earthquakes. The definition of a tsunami earthquake was originally proposed by Kanamori (1972): “an earthquake that generates a tsunami of significant magnitude relative to its surface wave magnitude M_s .” Assuming that the surface wave magnitude M_s is equivalent to the M_w , subsequent studies (Flores-Ibarra et al., 2025; Venkataraman & Kanamori, 2004) have shown that tsunami earthquakes have several distinct characteristics compared with typical earthquakes: (a) larger fault slip near the trench resulting in significant surface uplift; (b) relatively low rupture velocities, typically in the range of 1–2 km/s; (c) rupture durations longer than those of regular earthquakes with similar M_w ; and (d) scaled energy E_R/M_0 , defined as the ratio of radiated energy to seismic moment, to be substantially smaller and typically ranging from 7.0×10^{-7} to 3.0×10^{-6} . In particular, low E_R/M_0 values indicate that the earthquake radiates relatively little energy despite generating large fault slip and significant tsunami amplitudes, implying that a large portion of the energy is consumed as fracture energy. To our knowledge, while a few studies (Q. Meng & Duan, 2023; Q. Meng et al., 2022) have attempted to simulate the characteristics of tsunami earthquakes using dynamic models, no previous studies have successfully reproduced the observed range of scaled energy in their models.

To simulate tsunami earthquakes with the aforementioned characteristics, we modify several key parameters in our dynamic rupture model. First, the elastic wave speeds are reduced to 2.8 km/s for P-waves and 1.6 km/s for S-waves across the entire domain. These reduced velocities are intended to reflect the presence of a low-rigidity medium, such as an accretionary wedge, where seismic velocities are known to be significantly lower (e. g., Sallarès & Ranero, 2019). Second, to achieve low scaled energy (E_R/M_0), we vary the slip-weakening distance D_c across a broad range (0.3–7.2 m), while also adjusting the static and dynamic friction coefficients (μ_s and μ_d) and the fault size (Table 2). Following extensive parameter exploration (Figure S1 in Supporting Information S1), we successfully simulate an $M_w = 6.5$ tsunami earthquake (Sim #7) with a scaled energy of $E_R/M_0 = 1.7 \times 10^{-6}$, consistent with observational estimates.

Figure 9 presents the rupture dynamics and surface ground motions for the tsunami earthquake model (Sim #7), and for a typical thrust earthquake model (Sim #8). While tsunami earthquakes often occur at shallower depths with dip angles less than 30° , we adopt the same dip angle in both cases to facilitate a direct comparison of simulation results. The fault dimensions are 53 km $\times$ 15 km for Sim #7 and 29 km $\times$ 14.5 km for Sim #8. The stress drop and E_R for Sim #7 are 0.6 MPa and 1.2×10^{13} J, respectively, while those for Sim #8 are 1.2 MPa and 4.6×10^{13} J. The rupture velocity in Sim #7 is 1.2 km/s, substantially slower than the 3.0 km/s observed in Sim #8, primarily due to differences in the prescribed elastic wave speeds (Table 2). This, in turn, results in markedly different rupture durations: 60 s for Sim #7 and 15 s for Sim #8 (Figures 9a–9c, 9j and 9k). The maximum fault slip is 3.0 m for Sim #7, nearly four times greater than 0.8 m simulated in Sim #8 (Figures 9d and 9l). Finally, the local slip in Sim #7 barely exceeds the characteristic slip distance ($D_c = 2.9$ m) (Figures 9e and 9f), indicating that most of the available energy is consumed in the fracturing process. This leads to significantly lower radiated energy compared to Sim #8. Although the two scenarios have similar M_w , the reduced radiated energy in the tsunami earthquake reflects increased energy dissipation during rupture.

Figures 9g and 9o show the snapshots of U' for Sim #7 and Sim #8, respectively. Due to the larger fault and domain size in Sim #7, the ranges of the X and Y axes differ between the two panels. The extent of large U' in the Y – direction above the fault is similar in both cases, reflecting their comparable fault widths. However, the longer fault in Sim #7 produces a broader region of elevated U' along the X – direction. The peak U' values for both Sim #7 and Sim #8 are ~ 9 cm/s, notably smaller than those observed in the other $M_w = 6.5$ simulations (Figures 9h and 9p). These values represent near-field ground motion directly above the rupture, whereas commonly reported smaller peak ground motions for tsunami earthquakes are based on far-field (on-land) observations that are influenced by propagation through low-rigidity and attenuating near-trench materials. The final vertical displacements of (U) are 1.2 m for Sim #7 and 0.4 m for Sim #8 (Figures 9i and 9q), consistent with the larger slip near the trench in the tsunami earthquake scenario.

Figure 10 shows atmospheric simulation results for Sim #7 and Sim #8. Sim #8 has the smallest stress drop among thrust earthquakes in Nozuka et al. (2024) and in this study. Panels (n) and (o) show Y – Z slices of $|W|$, and panel (q) presents normalized temporal signals of W at various altitudes. AW dynamics in Sim #8 resemble those of

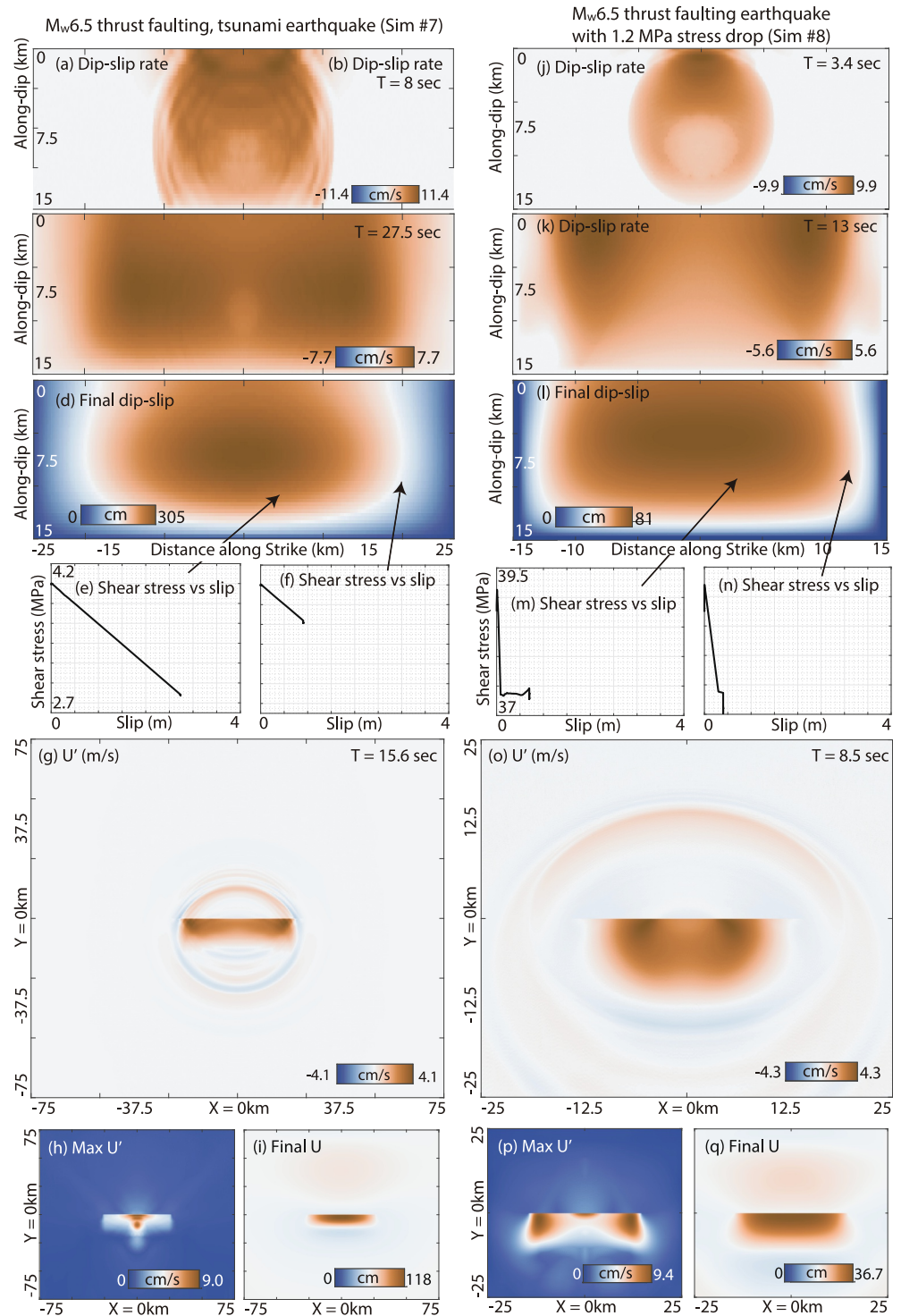


Figure 9. Earthquake rupture dynamics and associated surface ground motions for M_w 6.5 (a–i) tsunami earthquake (Sim #7) and (j–q) thrust earthquake with a stress drop of 1.2 MPa (Sim #8). (a–c) Show time snapshots of dip-slip rates for Sim #7, with the final dip-slip distribution in (d). (e, f) Display shear stress versus slip at selected on-fault receivers. (g) Illustrates the evolution of vertical surface velocity fields (U') for Sim #7, while (h, i) present peak $|U'|$ and the final vertical surface displacement (U), respectively. Similarly, (j, k) show time snapshots of dip-slip rates for Sim #8, with the final distribution in (l). (m, n) Display shear stress versus slip at selected receivers. (o) Illustrates the evolution of U' , and (p, q) present peak $|U'|$ and the final vertical displacements for Sim #8.

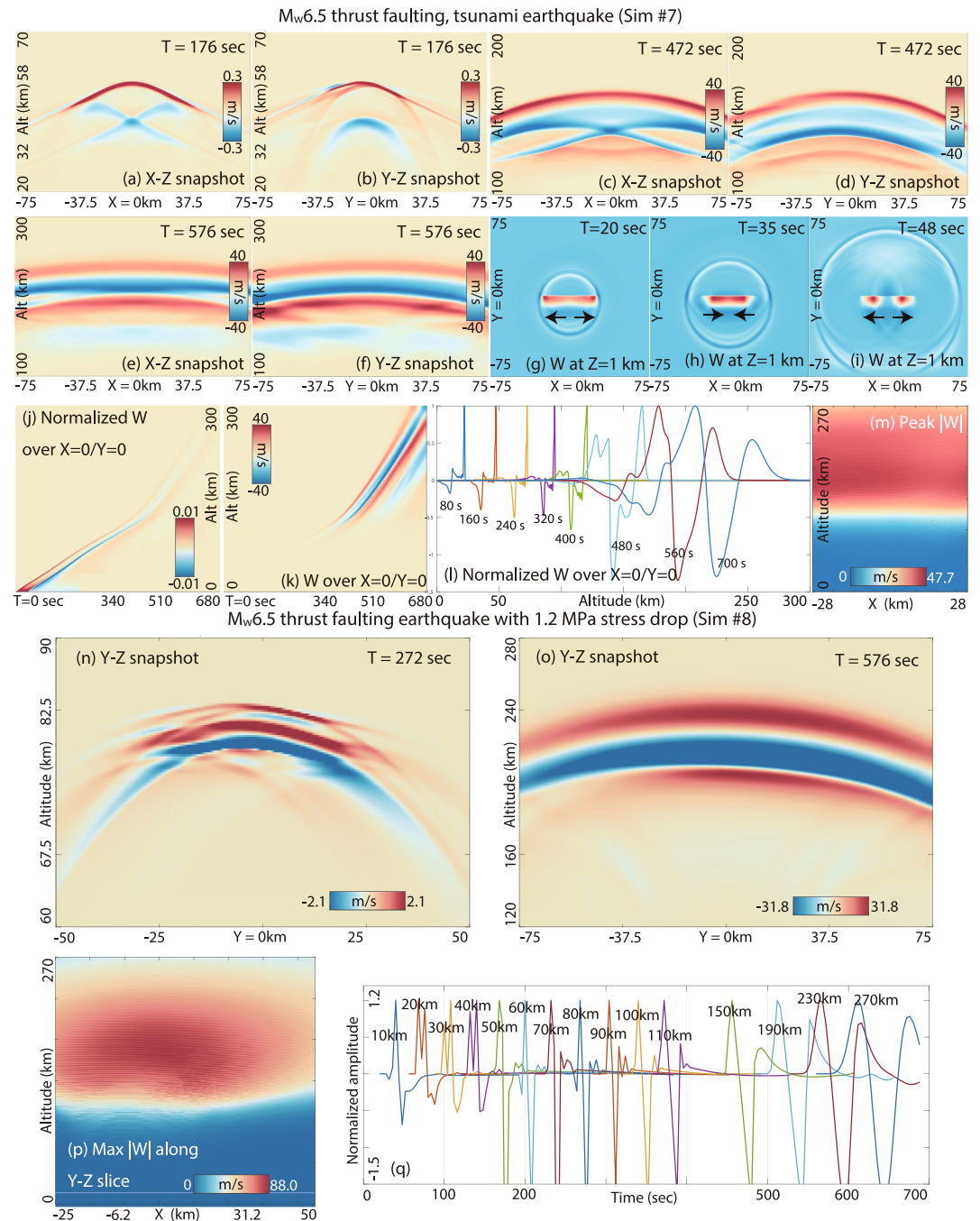


Figure 10. Results of acoustic wave (AW) simulations generated by M_w 6.5 (a–m) tsunami earthquake (Sim #7) and (n–q) thrust earthquake with a stress drop of 1.2 MPa (Sim #8). (a–f) Show snapshots of W at three different times along the X – Z / Y – Z transects. (g–i) Illustrate snapshots of W sliced horizontally at 1 km altitude. (j, k) Display normalized (by density) and absolute values of W at the $X = 0/Y = 0$ location over time. (l) Shows spatial signals of W at $X = 0/Y = 0$ for different times. (m) Presents peak amplitudes of $|W|$. In panel (f), strong waves near the left and right domain boundaries (secondary positive phase) are visible due to reflections; to minimize this effect, the peak $|W|$ in (m) is calculated over a narrower region. (n, o) Show snapshots of W at two different times from Sim #8. (p) Presents peak amplitudes of $|W|$ along an X – Z slice, and (q) shows temporal signals of W at various altitudes over the $X = 0/Y = 0$ location.

other thrust earthquakes, with surface-generated linear AWs featuring dominant positive leading phases, which evolve into shocks at ~ 100 km and form N-waves in the thermosphere. AWs reach peak amplitudes of 88 m/s at 166 km and 48 m/s at 250 km altitude (Figure 10p).

In contrast, AW dynamics from the tsunami earthquake (Sim #7) are more complex. Slow rupture propagation with a ~ 60 s period generates intricate AW packets. Figures 10g–10i show W at 1 km altitude, depicting AWs generated outward from the center of the domain (due to bilateral rupture expansion), followed by more concentrated AWs above the epicentral area and renewed expansion at ~ 50 s. This produces large-amplitude, leading positive-phase AWs, trailed by smaller-amplitude AW packets moving toward and away from $X = 0$, $Y = 0$ (Figure 10a). These complex shapes of AW packets persist up to the thermosphere at 150 km (Figure 10c), forming N-wave only above ~ 200 km (Figures 10e and 10f). Figures 10j and 10k illustrate the temporal evolution of W at $X = 0$, $Y = 0$, and Figure 10l shows normalized $|W|$ along the vertical profile, highlighting AW packet merging into an N-wave from initially separate shocks propagating far enough apart. Notably, a secondary positive shock, larger than the leading shock, arises from the complexity of ~ 60 s duration AW packet. In Sim #7, thermospheric AW periods range from 60 to 80 s, comparable to Sim #8. At the same time, peak $|W|$ values reach 47.7 m/s at 164 km and 38.9 m/s at 250 km, which are 20%–50% lower than those in Sim #8 at thermospheric altitudes, consistent with the lower radiated energy of the tsunami earthquake despite similar M_w .

4. Discussion

In this section, we summarize and analyze the results of the simulations discussed above to address the main question posed: to what extent do the AWs reaching the upper atmosphere differ among various earthquake source scenarios? We focus both on the qualitative differences of AWs and on their quantitative characteristics.

Supershear rupture earthquakes are seismically significant events due to their potential to generate intense and long-period ground motions through the formation of Mach waves (e.g., Bernard & Baumont, 2005; Dunham & Archuleta, 2005; Dunham & Bhat, 2008). Back-projection imaging techniques have frequently been used to infer the occurrence of supershear rupture propagation during large earthquakes (e.g., Ishii et al., 2005; Walker & Shearer, 2009). However, considerable uncertainties remain in the inferred rupture speeds, as the relationship between back-projection results and actual rupture parameters is not fully understood. Our simulations suggest that Mach waves generated by supershear ruptures produce AWs with distinct characteristics compared to those generated by subshear ruptures. In particular, we found earlier arrivals of AWs in the case of supershear rupture (~ 12 s), which are expected to be discernible based on temporally high-resolution GNSS TEC observations. Likewise, we find that supershear rupture produces AWs with amplitudes up to $\sim 20\%$ larger. These differences in AW signals in the upper atmosphere may provide an independent means to infer supershear rupture propagation.

We further investigated the question of how distinctively do different faulting mechanisms influence AW generation and propagation to the upper atmosphere. Leading negative-phase AWs of dominant amplitude, generated at the initial subsidence motion during a normal fault earthquake scenario, undergo marked distortion, and transform into an N-wave. This results from different propagation speeds of positive and negative shocks, formed below ~ 100 km altitude and their subsequent merging to N-wave. At the same time, the amplitudes of the resulting N-waves are approximately half those in the case of a thrust fault M_w 6.5 earthquake. This is consistent with the findings of Nozuka et al. (2024), which found similar AW evolution dynamics from reversely polarized seismic wave imprints on the surface in their strike-slip case study. These results suggest that polarity information inferred from GNSS TEC signals can be substantially modified during the upward propagation of AWs, implying limitations in directly relating TEC polarity to seismic wave polarity as discussed by Astafyeva and Heki (2009), while noting that our simulations are limited to neutral atmospheric wave dynamics. As we demonstrate for a normal-fault case, which produces AWs with a pronounced negative leading phase at the surface (in contrast to the strike-slip scenarios considered by Nozuka et al. (2024)), nonlinear evolution leads to the formation of N-waves even for earthquakes near the detection threshold of TEC (M_w 6.0–6.5). We therefore expect that for larger-magnitude earthquakes, the formation of N-waves is ubiquitous, consistent with previous studies (Lonzaga et al., 2015; Rogers & Gardner, 1980; Scott et al., 2017). We find that the leading negative phase of TEC signals for the normal-faulting scenarios could instead have resulted from a phase cancellation effect, as demonstrated and discussed by Inchin et al. (2020, 2024).

Recent studies used analytical solutions or linear models to simulate the vertical propagation of seismically induced AWs to the thermosphere (Fu et al., 2025; Li et al., 2025; Sanchez et al., 2025). Based on our results, we infer that while these approaches enabled rapid solutions for near-real-time applications, they overlook critical nonlinear AW evolution. For instance, in the normal-fault earthquake scenario discussed earlier, only nonlinear models can capture the transition of negative leading-phase AWs into shocks and subsequent N-waves. As a

result, neglecting nonlinear effects could lead to inaccurate estimates of AW amplitudes, periods, and arrival times of associated AW signals in GNSS TEC or other observations, which are essential for inferring earthquake source characteristics.

Next, we performed heterogeneous rupture scenario simulations with two different correlation lengths and found that AW signals in the thermosphere are less sensitive to the short-scale complexities in seismic waves. This suggests that a sufficiently accurate modeling of coseismic signals in the upper atmosphere may not require precise modeling of earthquake ruptures for short-period ground motions of less than a few seconds. This was also supported by the modeling results of Inchin et al. (2024), where seismic waves and AWs incorporated into simulations are resolved down to ~ 3 s period. Our new modeling results suggest that coseismic AW observations at thermospheric heights (i.e., 150–300 km) may have limited sensitivity to small-scale details of the rupture process (seismic waves with the spatial scales of $\lesssim 10$ km), but provide a clear context of seismic waves of longer periods. Although not yet investigated here, measurements at lower altitudes may also provide insight into signals of sufficient intensities, such as via targeted observations from tropospheric or stratospheric platforms (e.g., Brissaud et al., 2021), future mesospheric airglow imaging (e.g., Inchin et al., 2022), or by lower-ionospheric radio remote sensing (e.g., Obenberger et al., 2023).

Furthermore, we compared AWs from a typical thrust earthquake and a tsunami earthquake. Despite comparable peak surface vertical velocities, thermospheric AW amplitudes in Sim #7 are 20%–50% lower than in Sim #8, while signal periods remain similar. The prolonged rupture of the tsunami earthquake generates complex AW packets, resulting in intricate signal shapes even at 150 km altitude, unlike the distinct N-wave shapes produced by thrust earthquakes with shorter rupture durations. This suggests that anomalously low thermospheric AW amplitudes, combined with periods comparable to those of thrust-earthquake AWs, may indicate a tsunami earthquake. We note that here we used a M_w 6.5 thrust earthquake with just a 1.2 MPa stress drop, and earthquakes with larger stress drops, as demonstrated by Nozuka et al. (2024), produce AWs of even larger amplitudes. At the same time, normal-faulting earthquakes, as discussed above, could also produce comparable AW characteristics. Thus, we refrain from drawing further definitive conclusions and recommend future comprehensive studies of tsunami earthquakes and their upper-atmosphere AW signals.

Nozuka et al. (2024) found a correlation between E_R in their dynamic rupture models and the resulting AW amplitudes in the thermosphere. In this study, we extended their analysis by incorporating the scenarios investigated here, including normal faulting (Sim #3), heterogeneous ruptures (Sim #5 and Sim #6), and a tsunami earthquake (Sim #7). Figure 11a shows the relationship between E_R and the maximum $|W|$ across the entire atmospheric domain, while Figure 11b focuses on $|W|$ at 250 km altitude - the altitude of commonly dominant TEC signals (Inchin et al., 2024). A strong correlation between E_R and AW amplitudes, except for Sim #3, reinforces the conclusion of Nozuka et al. (2024) that E_R is a key parameter controlling AW generation. Although Nozuka et al. (2024) assumed uniform fault planes with the same rigidity of elastic medium and identical shear and normal stress conditions across simulations, our study incorporated rupture heterogeneities, variations in rigidity, and differences in stress conditions. We suspect that inconsistency between normal fault scenario simulation and the correlation lies in the marked nonlinear evolution of AWs, from leading negative phase AWs in the lower atmosphere, to N-waves in the thermosphere. We speculate that cases such as normal faults should be investigated separately from thrust or strike-slip earthquakes, as earthquake mechanism plays a crucial role in AW signal amplitudes in the thermosphere.

Finally, to relate our inferences to observations, we compare energy magnitude (M_e) and moment magnitude (M_w) with relative vTEC perturbation amplitudes, expressed as a percentage of absolute vTEC (Figure 12), for several normal-faulting earthquakes with identifiable coseismic vTEC signals (Table S1 in Supporting Information S1). Three normal-faulting events with detectable signals, adapted from Perevalova et al. (2014), exhibit substantially lower relative vTEC perturbations than thrust earthquakes (Table S1 in Supporting Information S1), consistent with our modeling results. In addition, our analysis of recent normal-faulting earthquakes revealed no detectable vTEC signals for the 2016 M_w 6.6 and 6.2 Italian earthquakes and the 2011 M_w 6.6 Japanese earthquake (Table S1 in Supporting Information S1). This is consistent with the findings of Perevalova et al. (2014), who reported no detectable TEC signals for normal-faulting earthquakes with $M_w \leq 6.5$. Importantly, the absence of detectable signals for these three events persists despite favorable line-of-sight (LOS) geometries, suggesting that the lack of detectable signals is unlikely to result from observational limitations.

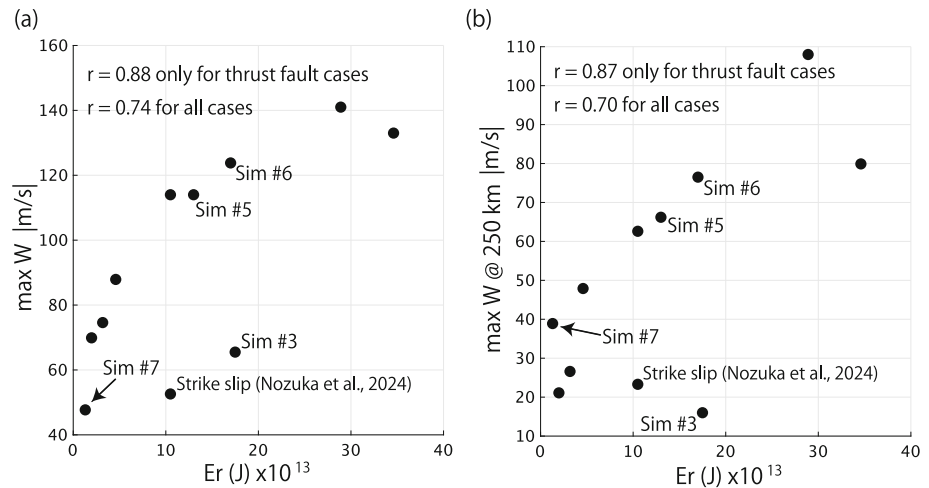


Figure 11. Correlations between (a) the absolute peak vertical fluid velocity amplitudes ($|W|$) of acoustic waves (AWs) and (b) the peak W at 250 km altitude, analyzed with respect to earthquake radiated energy E_R for Sim #3, Sim #5, Sim #6, and Sim #7, in addition to all scenarios discussed in Nozuka et al. (2024). Only M_w 6.5 earthquake scenarios are included to enable comparison across events with similar magnitude and to isolate the effects of source characteristics on AW amplitudes. Pearson's correlation coefficients (r) are provided for all cases, as well as for thrust events only, as indicated in each panel.

Additionally, Figure 12 includes observations from the 2025 Myanmar supershear earthquake analyzed by K. Heki and Zhan (2026). The results presented by Nozuka et al. (2024), which are also consistent with the conclusions of K. Heki and Zhan (2026), demonstrated that strike-slip earthquakes commonly produce smaller vTEC perturbation amplitudes than thrust earthquakes because dominant horizontal surface velocities generate weaker AWs in the atmosphere. Interestingly, the 2025 Myanmar earthquake generated TEC fluctuations of up to $\sim 2.3\%$, comparable to those of thrust earthquakes with similar energy or moment magnitude. This observation may support our conclusion that supershear earthquakes can generate relatively large-amplitude TEC signals. However, we refrain from further speculation because the 2025 Myanmar earthquake is effectively the only event for which clear near-source TEC signals have been reported, providing limited statistical constraints. Similarly, although K. Heki et al. (2022) noted that TEC amplitudes from the 2010 Mentawai tsunami earthquake are

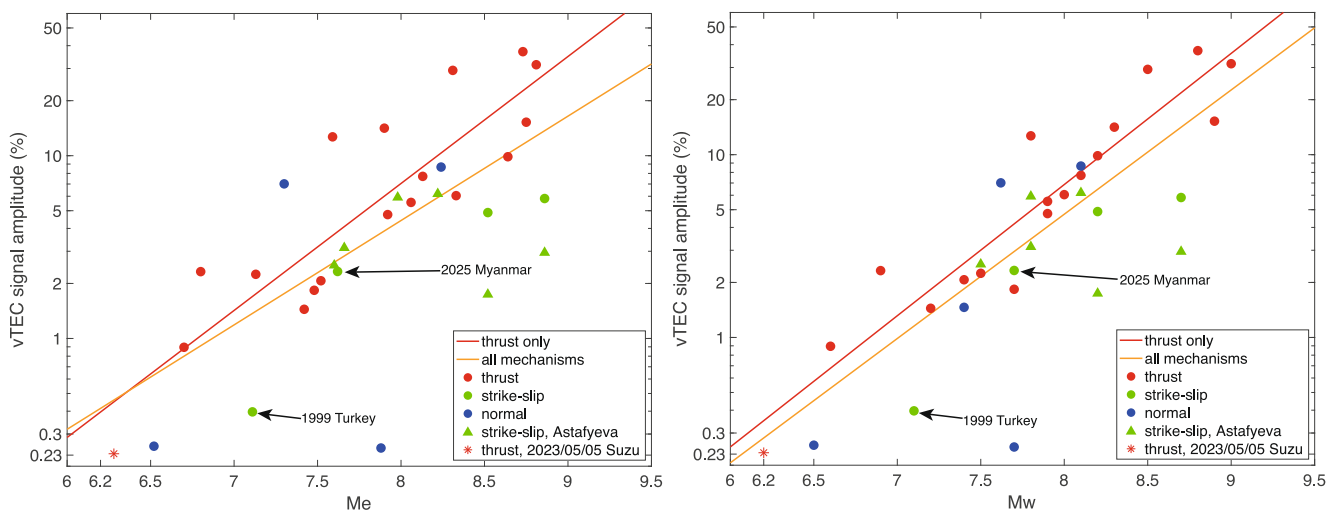


Figure 12. Correlation between energy magnitude (M_e), moment magnitude (M_w), and Global Navigation Satellite System vTEC perturbation amplitudes, expressed as a percentage of the absolute vTEC. Red, green, and blue symbols denote vTEC perturbation amplitudes for thrust, strike-slip and normal-faulting earthquakes, respectively. Green triangles indicate vTEC perturbation amplitudes for strike-slip earthquakes reported by Astafyeva et al. (2013). These data are adapted from Figure 8 of Nozuka et al. (2024), with additional data added from vTEC values reported by Perevalova et al. (2014) and K. Heki and Zhan (2026) (Table S1 in Supporting Information S1). The red dashed line shows the best-fitting relation, with both slope and intercept determined by linear regression using the 18 thrust-fault earthquake data points. The yellow dashed line represents the best-fitting relation obtained by linear regression using all data shown in this figure.

comparable to those of typical thrust earthquakes, the current scarcity of vTEC observations for tsunami earthquakes limits the statistical robustness of such comparisons.

We note that the comparisons discussed above may be affected by insufficient TEC coverage in near-source regions, limitations in LOS geometries for detecting the largest-amplitude signals, ionospheric variability, and geomagnetic field effects. We anticipate that the continued expansion of GNSS receiver networks will provide more comprehensive observational constraints on these relationships in the future.

5. Conclusions

We presented a comprehensive analysis of coupled solid Earth-atmosphere simulations, investigating the impact of earthquake sources on acoustic wave (AW) characteristics in the upper atmosphere. Incorporating dynamic earthquake source models, we simulated various scenarios, including sub- and supershear ruptures, normal and thrust faulting, heterogeneous fault slip and ruptures, and tsunami earthquakes. We focused on moderate-magnitude events, M_w 6.5 for thrust and M_w 7.1 for strike-slip earthquakes. This study focuses on the neutral atmospheric response and does not explicitly model ionospheric plasma or geomagnetic field effects. Rather than attempting to reproduce individual earthquake events, our objective was to identify robust physical relationships between rupture dynamics and thermospheric AW signatures under controlled source conditions. The results improve our understanding of the potential to infer AW source characteristics through various upper-atmospheric and ionospheric observations, including GNSS TEC, mesospheric airglow imagers, and ionosondes, by providing process-level constraints on the underlying AW dynamics.

Analysis of sub- and supershear earthquake scenarios revealed distinct thermospheric AW signals, enabling differentiation of rupture propagation through AW arrival times and amplitudes. Simulations of normal-faulting scenarios demonstrated the nonlinear evolution of AWs into N-waves, even for a M_w 6.5 earthquake, further highlighting the need for nonlinear simulations to accurately replicate AW signals in the upper atmosphere. Despite comparable magnitudes and stress drops, normal-faulting earthquakes would produce significantly weaker thermospheric AW amplitudes than thrust earthquakes, consistent with Perevalova et al. (2014) who noted that only large-magnitude normal earthquakes generate detectable TEC signals. We emphasize that these comparisons are qualitative, as direct TEC responses depend on additional ionospheric and geomagnetic factors not included in this study. Our analysis of the relationship between energy magnitude (M_e), moment magnitude (M_w), and relative vTEC perturbation amplitudes further supports these conclusions. Finally, anomalously low thermospheric AW amplitudes, despite periods comparable to thrust earthquakes, may indicate a tsunami earthquake. However, because similar characteristics can also arise from normal-fault earthquakes, we recommend future studies to identify distinct AW characteristics generated by tsunami earthquakes to assess the feasibility of classifying these events based on thermospheric signals.

Our modeling investigation of rupture heterogeneities also indicates that thermospheric AW signals are largely insensitive to small-scale (<10 km) seismic wave variations. Conversely, in the lower atmosphere (<100 km altitude), these variations are discernible at 80–100 km based on the analysis of AW characteristics, suggesting potential detectability using sensitive, high-resolution airglow imagers, but not GNSS TEC. Additionally, our findings reinforce Nozuka et al. (2024), confirming that radiated seismic energy (E_R), rather than moment magnitude (M_w), primarily governs AW amplitudes in the upper atmosphere.

We note, however, that although we addressed the most fundamental aspects of earthquake-atmosphere coupled processes, future research may further expand the investigation of the relationship between surface dynamics and AWs, focusing on their signatures in the upper atmosphere across a broader range of earthquake source scenarios. In particular, simulations with extended computational domains are needed to assess the impact of Mach and Rayleigh waves on long-range AW propagation across various earthquake scenarios (e.g., supershear and sub-shear). Likewise, future studies may target simulations of ionospheric plasma responses to AWs and the modeling of observations for detecting them under different ambient conditions, including day/night cases, solar maximum and minimum, geomagnetic conditions, spanning high, middle, and low latitudes. Finally, we believe that additional data-guided studies are required to test the applicability of our conclusions in realistic scenarios, thereby supporting or questioning these modeling parameter-based studies. Such efforts will ultimately improve our understanding of how atmospheric observations of seismically induced AWs can supplement routine seismological investigations of earthquake processes.

Conflict of Interest

The authors declare no conflicts of interest relevant to this study.

Availability Statement

The software used for earthquake source modeling and seismic wave propagation simulations, SPECfem3D, is publicly available at <https://geodynamics.org/resources/specfem3dcartesian>. The detailed workflow for simulating atmospheric AWs in the MAGIC model is provided in Text S4 in Supporting Information S1. The data sets and animations of seismic wave propagation and atmospheric simulations, as well as necessary scripts to read and plot the data, are available at Inchin (2026).

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