

Seismic Hazard on the Main Himalayan Thrust from Physics-Based Earthquake Simulations

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Abstract

Seismic hazard assessment in the Himalayan region remains highly uncertain due to the limited historical record and complex fault behaviour. To help address this, we present a 10,000-year long catalogue of synthetic earthquake ruptures on the Main Himalayan Thrust (MHT), one of the most hazardous continental fault systems on Earth. Simulations were performed by implementing geodetic models of the MHT's geometry and slip rate into the physics-based Rate-and-State Earthquake Simulator (RSQSim), which applies the concepts of rate and state-dependent friction to generate long-duration synthetic earthquake catalogues. The MHT catalogue we generated reproduces key characteristics of observed seismicity, including magnitude-frequency distributions, rupture extents, and spatial patterns along the MHT. A key result is that low-coupling zones, previously inferred from geodetic data, consistently act as rupture barriers in the simulations, effectively limiting the maximum magnitude to M_w 8.9. In addition, we implemented this MHT RSQSim catalog into a stochastic probabilistic seismic hazard assessment (PSHA) of Nepal and compared the hazard estimates to a conventional PSHA model. At 10% probability of exceedance (PoE) in 50 years, the maximum difference (RSQSim derived hazard - classical PSHA) in Peak Ground Acceleration (PGA) range from +0.1g (+20%) to -0.6g (-70%), while at 2% PoE in 50 years the differences are +0.3g (+30%) to -0.6g (-40%), and at 0.5% PoE in 50 years, it is +0.4g (+30%) to -0.7g (-40%). In relative terms, 84% of sites have an absolute hazard difference below 60% at 10% PoE in 50 years, while 84 % of sites have an absolute hazard difference below 30% for 2% and 0.5% PoE in 50 years. Our results suggest that physics-based simulations offer a valuable complement to conventional source models, particularly for faults with variable rheologies and limited earthquake records like the MHT.

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1 Introduction

The Himalayan mountain range is the most prominent surface expression of the ongoing collision between the Indian and Eurasian plates, active since the Eocene. The convergence rate between the Indian and Eurasian plates occurs at a rate of 40 mm/year, with approximately half accommodated by the Main Himalayan Thrust (MHT) (e.g., Bilham et al. 1997; Larson et al. 1999; Jouanne et al. 2004; Stevens et al. 2018; Dal Zilio et al. 2020). In turn, this convergence has been accommodated by a spectrum of seismic events along the MHT, ranging from blind thrust events, such as the 1833 M_w 7.5 $\pm$ 0.3 Nepal Earthquake and 2015 M_w 7.8 Gorkha Earthquake (Bilham, 1995; Elliott et al., 2016), to surface-rupturing megathrust events like the 1950 M_w 8.5 Assam Earthquake (Chen and Molnar, 1977), 1934 M_w 8.2 Bihar-Nepal Earthquake (Sapkota et al., 2012), and M_w 8.0 $\pm$ 0.5 Lo Mustang Earthquake in 1505 (Jackson 2002; Ambraseys and Jackson 2003). These seismic behaviours reflect the interplay between long-term

tectonic deformation and transient rupture processes that shape the Himalaya across multiple timescales (Dal Zilio et al., 2021).

Since 1800, earthquakes in the Himalayas have caused over 150,000 documented fatalities (Bilham, 2019). Accurate characterization of the MHT's earthquake rates, magnitudes, and rupture extents is thus critical for assessing seismic hazard in one of the world's most densely populated regions. However, forecasting future MHT seismicity is challenging due to the limited length and completeness of instrumental and historical earthquake records. While paleoseismic data can help extend these records further back in time, interpretation of these data in the MHT is often non-unique and debated (e.g., Kumar et al. 2006; Sapkota et al. 2012; Le Roux-Mallouf et al. 2020). Moreover, obtaining paleoseismic data in the Himalayas poses additional challenges due to its rugged and inaccessible topography and high erosion rates (Stevens et al., 2018), and that these records inherently miss blind earthquake ruptures that appear to be common along the MHT.

In this study, we examine if the physics-based earthquake simulator RSQSim can help address the gap be-

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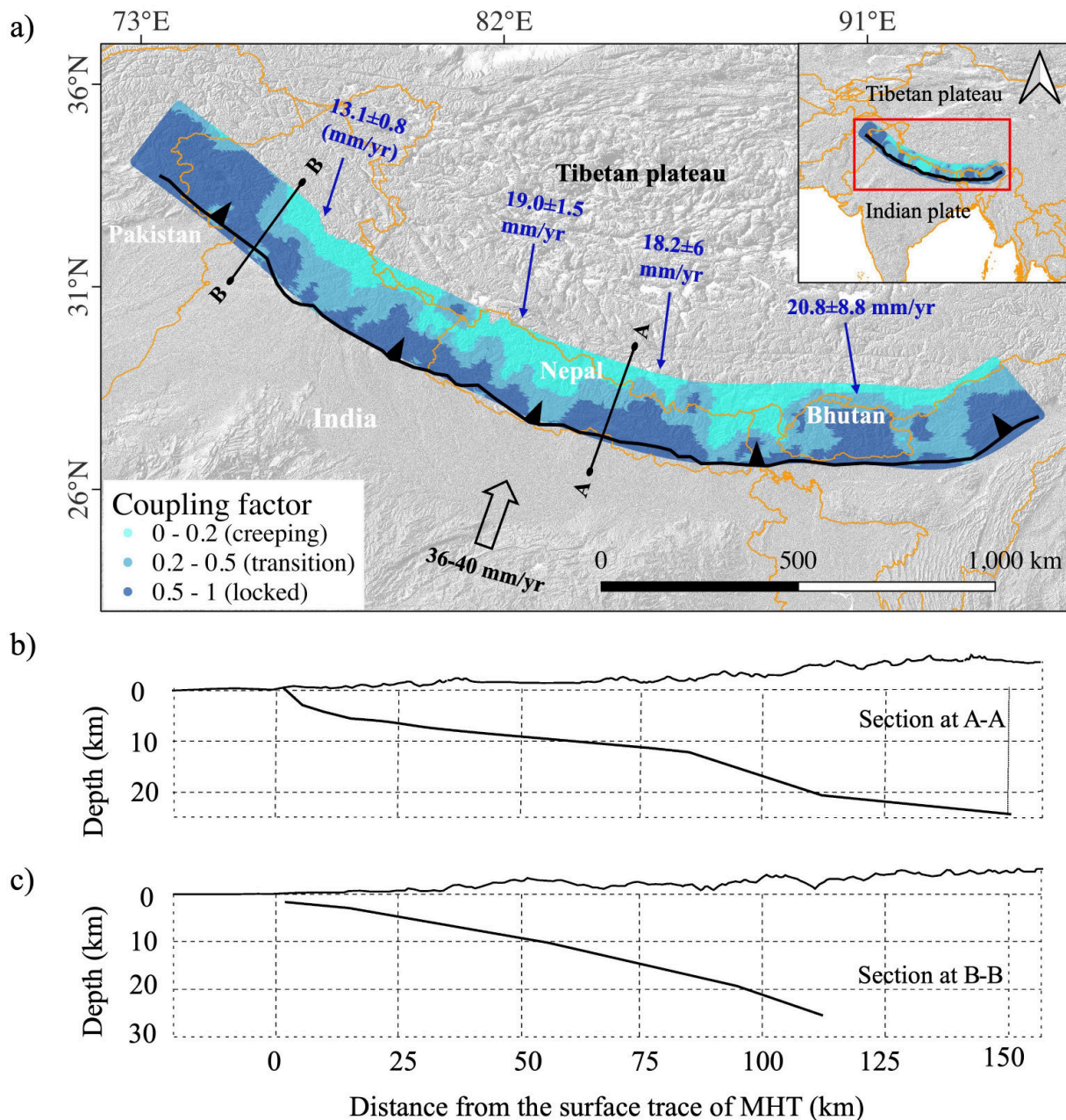


Figure 1 (a) Interseismic coupling factor and slip rates on the MHT (Dal Zilio et al., 2020). Creeping, locking, and transition zones are defined based on the coupling factor. The MHT surface trace is illustrated by a solid black line with barbs indicating the fault hanging wall. (b) Ramp-flat-ramp geometry of the MHT at A-A section after Elliott et al. (2016). (c) Planar geometry of the MHT at B-B section after O’Kane et al. (2022)

tween the MHT’s incomplete earthquake record and the needs of seismic hazard models. We begin by describing how geological, seismic, and geodetic data were used to constrain the MHT’s 3D geometry, slip rates, and frictional properties into RSQSim. We then evaluate the synthetic catalogue of MHT earthquakes produced by RSQSim by comparing its magnitude-frequency distribution (MFD) with historical and instrumental seismicity on the MHT. Additionally, we compared the spatial extent of rupture suggested by RSQSim with those observed in historical earthquakes in the Himalayas. In particular, we investigate whether previously inferred low-coupling zones —defined as areas with low ratios of slip deficit to long-term slip rate— act as barriers to large earthquake rupture propagation. Finally, we

generate stochastic probabilistic seismic hazard (PSH) maps from the RSQSim catalogue and compare them with previously published PSH model for Nepal.

2 The Rate and State Earthquake Simulator (RSQSim)

Multiple physics-based earthquake simulators are now available (Pollitz, 2012; Ward, 2012; Sachs et al., 2012). In this study, we selected RSQSim to model the long-term seismicity on the MHT due to its computational efficiency and its demonstrated ability to reproduce historical earthquake patterns across several regions (Shaw et al., 2018, 2022; Niroula et al., 2025; Herrero-Barbero et al., 2021). RSQSim is a 3D boundary element

Parameter	Values
Slip rates	13 mm/yr (Zone 1); 15 mm/yr (Zone 2); 18 mm/yr (Zone 3) and 30 mm/yr (Zone 4)
μ	0.2, 0.4, and 0.6 (adopted)
a and b values: locked zone (coupling factor ≥ 0.5)	0.001, 0.004
a and b values: transition zone ($0.2 < \text{coupling factor} < 0.5$)	0.001, 0.0015
a and b values: creeping zone (coupling factor ≤ 0.2)	0.01, 0.008
Lamé's constants	30 GPa
Shear and Normal Stress	60 MPa and 100 MPa

Table 1 Parameters adopted in the MHT RSQSim model. The distribution of slip rates, a and b values throughout the MHT is provided in the supplementary file (Fig. S2).

model that employs an approximation of the constitutive rate- and state-dependent friction law formulated by Dieterich (1979), Ruina (1983), and Rice (1983) to simulate seismicity across a network of mapped faults. Fault surfaces are discretized into either rectangular patches (Okada, 1992) or triangular elements (Gimbutas et al., 2012), depending on the geometry. The shear and normal stress acting on each patch progressively evolve during the simulations based on a combination of tectonic loading and stress interactions with nearby slipping patches.

Based on these stress magnitudes, RSQSim will assign each patch into one of three states during each simulation cycle: State 0 (Healing), State 1 (Nucleation), and State 2 (Seismic Rupture) (Richards-Dinger and Dieterich, 2012). In State 0, the fault patch is locked because the shear stress remains below the static friction strength. In State 1, the shear stress exceeds the static friction, initiating slip on the patch. Once the slip velocity on a fault element increases to the maximum value defined by the Brune (1970) shear impedance relation, the fault element enters State 2, and it can load neighbouring elements. Patches return to State 0 when shear stress drops below the static frictional limit.

The seismic moment released by a patch during an event is determined by multiplying the shear modulus, area of the patch, and coseismic slip. Summing the seismic moments of all rupturing patches gives the total seismic moment, which is then converted into moment magnitude using standard scaling relations (Hanks and Kanamori, 1979).

3 Main Himalayan Thrust (MHT) geometry, slip rates, interseismic coupling factor, and coefficient of friction

The MHT is the principal active structure along the Himalayan arc, reaching the surface as the Main Frontal Thrust (MFT, Fig. 1a; Lavé and Avouac, 2001). The MHT is approximately 2400 km long, and the seismogenic down-dip extent is 150 km, reaching a depth of ~ 25 km. Its geometry, as constrained by geodetic, geological, geomorphic, and geophysical analysis (Elliott et al., 2016) and analysis of the aftershock sequence following the 2015 Gorkha earthquake (Duputel et al., 2016), has a ramp-flat-ramp geometry on its eastern section (Fig.

1b). However, further west, in the Jammu and Kashmir region, it has a planar geometry (O'Kane et al., 2022, Fig. 1c). The geometry of the MHT between these sections is unknown. Whilst some studies have used the flat-ramp-flat geometry to simulate MHT earthquake cycles (e.g., Dal Zilio et al., 2019; Sathiakumar and Barbot, 2021), interseismic coupling studies on the MHT have assumed a simplified planar geometry with a constant fault dip of 10° (e.g., Ader et al., 2012; Stevens and Avouac, 2015; Dal Zilio et al., 2020).

The convergence rate between the Indian and the Tibetan plates is about 40 mm/yr (e.g., Bilham et al., 1997; Larson et al., 1999; Jouanne et al., 2004). Geodetic models indicate that the MHT accommodates $\sim 50\%$ of this convergence rate and that slip rates increase from west to east by varying amounts: from 13.3 ± 1.7 mm/yr to 21.2 ± 2.0 mm/yr (Stevens and Avouac, 2015), from 13.1 ± 0.8 to 20.8 ± 8.8 (Dal Zilio et al., 2020), or from 15.3 to 20.2 (Lindsey et al., 2018). All these slip rates are consistent with the long-term geological and geomorphic slip rates (e.g., Stevens and Avouac, 2015).

There are several geodetically derived coupling model for the Himalaya region (e.g., Ader et al., 2012; Sreejith et al., 2018; Stevens and Avouac, 2015; Li et al., 2018; Dal Zilio et al., 2020; Tabei et al., 2024). Most of these models are, however, regional in extent; and so we focus on two models that extend throughout the Himalaya (Stevens and Avouac, 2015; Dal Zilio et al., 2020). In the case of Stevens and Avouac (2015) the MHT is inferred to uniformly locked along its length and to a down-dip distance of about 100 ± 20 km. At this downdip extent, there is a sharp transition between the MHT's locking and creeping zones. More recently, Dal Zilio et al. (2020) used a fully Bayesian approach that indicated variable interseismic coupling along the MHT, with four highly coupled patches separated by three low-coupling zones (Fig. 1a). These three low-coupling zones also correspond to regions with lower instrumental seismicity record since 1950 (Fig. 3). Furthermore, unlike the Stevens and Avouac (2015) model, this model indicated gradual variations in coupling between locking and creeping zones on the MHT.

4 MHT RSQSim model

We used RSQSim to simulate a 15,000-year record of MHT seismicity. To avoid artifacts associated with

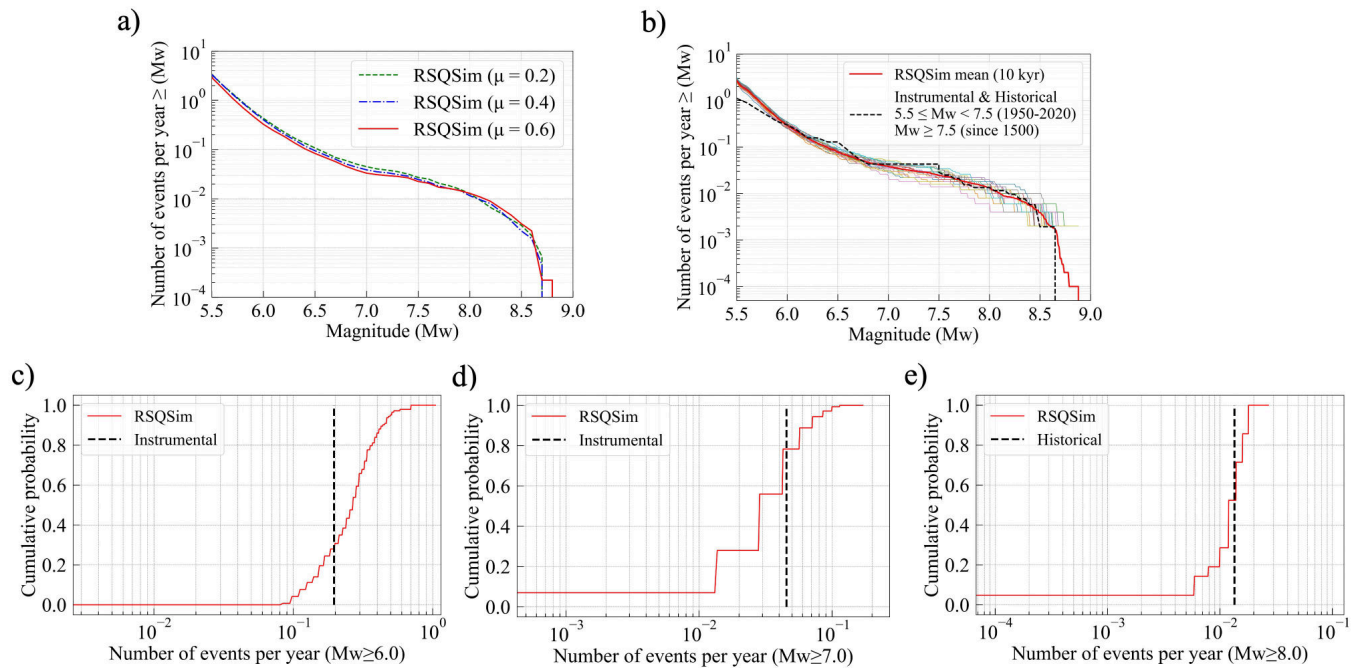


Figure 2 (a) Comparison of MFDs of synthetic earthquakes from the MHT RSQSim model for $\mu = 0.2, 0.4$, and 0.6 . (b) Comparison of the MFD of synthetic earthquakes from RSQSim (20 x 500 years sub-catalogs) with instrumental earthquakes $5.5 \leq M_w < 7.5$ (1950 - 2020) and historical earthquakes $M_w \geq 7.5$ on the MHT since 1500. The red line shows mean MFD from RSQSim, and the black line shows the instrumental and historical earthquakes. The historical and instrumental earthquake MFDs are obtained from [Stevens and Avouac \(2016\)](#) and the International Seismological Centre (ISC) catalogue ([Di Giacomo et al., 2015](#)). (c), (d), and (e) show cumulative probability distribution for event numbers per year $M_w \geq 6.0$, $M_w \geq 7.0$, and $M_w \geq 8.0$, respectively. The vertical dashed lines show the instrumental and historical earthquake rates.

model initialization, we discarded the first 5,000 years as a ‘spin-up’ period, during which RSQSim evolves toward a statistically steady state ([Shaw et al., 2022](#); [Hughes et al., 2023](#)). To implement the MHT’s interseismic coupling factor, slip rate, and geometry into the RSQSim, we adopted the most recent geodetic coupling model ([Dal Zilio et al., 2020](#)). A requirement of using this model is that the MHT has a uniform planar geometry with a dip of 10° degrees ([Dal Zilio et al., 2020](#)). The fault surface was discretized at 4 km resolution, yielding approximately 70,000 fault patches. Based on the MHT coupling factors, we defined locking ($\text{coupling factor} \geq 0.5$), transition ($0.2 < \text{coupling factor} < 0.5$), and creeping ($\text{coupling factor} \leq 0.2$) zones (Fig. 1a). Following previous RSQSim simulations (e.g., [Hughes et al., 2023](#); [Delogkos et al., 2023](#)), we derived the a and b constants of the rate and state friction equation ([Dieterich, 1979](#); [Ruina, 1983](#)) from an iterative approach that selects these values from those that result in earthquake that are most consistent with empirical magnitude area-scaling relations of continental ([Stirling et al., 2023](#); [Thingbaijam et al., 2017](#); [Allen and Hayes, 2017](#)) and subduction zone earthquakes (e.g., [Shaw et al., 2018, 2022](#); [Herrero-Barbero et al., 2021](#); Table 1, Fig. S1).

It is common in RSQSim and other physics-based simulations to use globally calibrated friction parameters ([Herrero-Barbero et al., 2021](#); [Shaw et al., 2022](#); [Hughes et al., 2023](#)). However, in the case of the MHT, studies have inferred a range of estimates for its static and effective friction strength. [Cattin and Avouac \(2000\)](#) estimated the apparent friction coefficient to be ~ 0.3 for

the flat segment and ~ 0.6 for the ramp segment of the MHT. By contrast, [Bollinger et al. \(2004\)](#) suggested that the friction on the MHT is below 0.3 and [Herman et al. \(2010\)](#) proposed an effective friction coefficient of less than 0.07. To explore the influence of this uncertainty on the simulations, we generated RSQSim catalogues with the coefficient of dynamic friction μ set to 0.2, 0.4, and 0.6 (Table 1). The results indicated that the model with $\mu = 0.6$ exhibited slightly lower earthquake rates for magnitudes ≤ 8.0 compared to the models with μ values of 0.2 and 0.4 (Fig. 2a). However, differences across the three magnitude-frequency distributions (MFDs) were minor (Fig. 2a), and so for simplicity, the following analysis focuses on the RSQSim catalogue generated with $\mu = 0.6$. The complete list of input parameters is provided in Table 1 and in the supplementary materials (Fig. S2).

5 Model evaluation

We first compare the synthetic catalogue of MHT earthquakes generated by the RSQSim against historical and instrumental seismicity rates and rupture extents. This is necessary, as our RSQSim simulations are a simplified model of the MHT’s earthquake cycle, and we don’t expect it to fully replicate its seismicity. Instead, we aim to show that even this simplified model can capture some natural behaviour of earthquake occurrence (e.g., [Shaw et al., 2022, 2018](#); [Field, 2019](#)). Based on these tests, we then examine emergent features within the MHT RSQSim catalogue that provide new insights into its seismicity and seismic hazard, such as its maximum

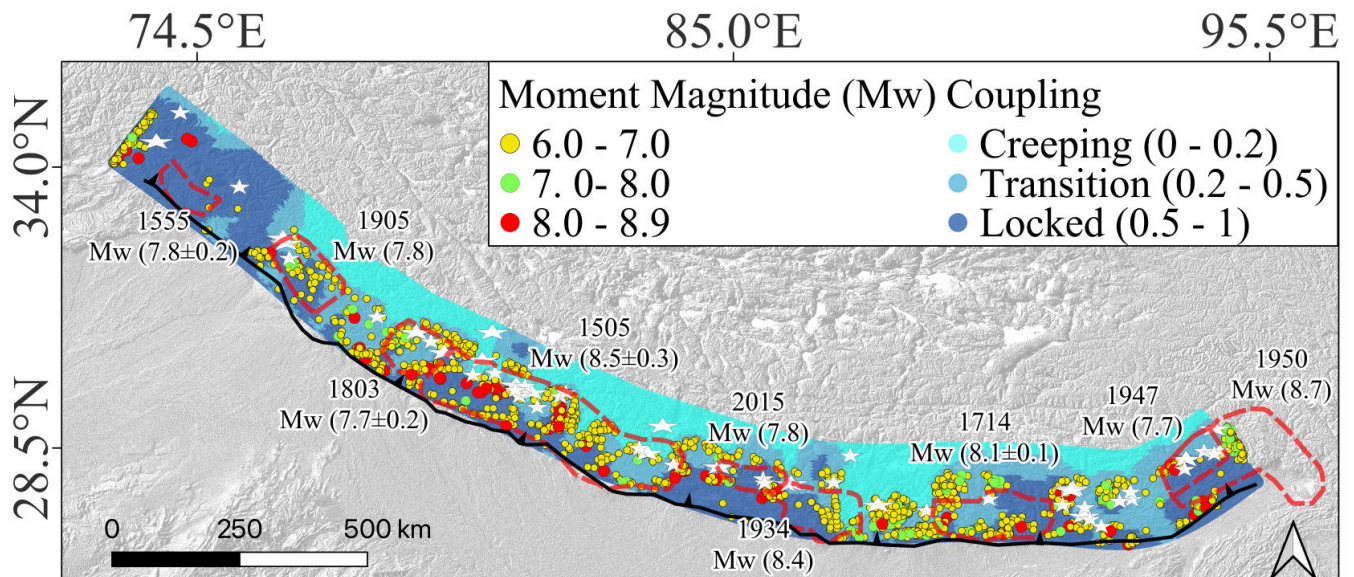


Figure 3 Synthetic seismicity ($M_w \geq 6.0$, 5,000 years simulation time) from the MHT RSQSim model plotted with 70 years (1950-2020) of instrumental seismicity ($M_w \geq 5.5$, white stars), historical earthquake ruptures (red dashed polygon) since 1500 CE after Bilham (2019) and the interseismic coupling factor from Dal Zilio et al. (2020). The MHT surface trace is illustrated by a solid black line with barbs indicating the fault hanging wall. The instrumental data are from the International Seismological Centre (ISC) catalogue (Di Giacomo et al., 2015).

magnitude, recurrence interval, and the existence and location of any along-strike rupture barriers.

5.1 Comparison of MFDs from the MHT RSQSim Catalogue to historical and instrumental seismicity

One approach to test the reliability of the synthetic earthquake catalogues is to compare subsamples of their MFD with observed seismicity (e.g., Stirling and Gerstenberger, 2018; Shaw et al., 2022; Williams et al., 2023; Niroula et al., 2025). Since historical and instrumental catalogues have different periods and magnitudes of completeness, we considered $M_w \geq 7.5$ earthquakes documented since 1500 CE for historical events (Stevens and Avouac, 2016; Bilham, 2019), and for instrumental seismicity, $M_w \geq 5.5$ events in the ISC catalogue since 1950. This latter constraint is based on a significant increase in the number of Himalayan events in the ISC catalogue after 1950 (supplementary file; Fig. S3). All ISC catalogue events <25 km depth and <150 km across strike from the MHT surface trace are considered in this analysis. This dataset likely represents an upper bound on MHT seismicity, as it inherently include events that nucleate above and below it, and which we could not exclude due to depth uncertainties. Assuming that the ISC catalogue is complete for $5.5 \leq M_w < 7.5$ events between 1950-2020 and historical is complete since 1500 for $M_w \geq 7.5$, we combine instrumental and historical earthquakes and compared with the 20 x 500 RSQSim sub-catalogues. In addition, we show the cumulative distribution function (CFDs) for the annual rate of $M_w \geq 6.0$, 7.0, and 8.0 earthquakes of these subsamples, and compare them to the instrumental and historical records.

Figure 2 compares the MFDs from the MHT RSQSim

catalogue with historical and instrumental catalogues. Although the MFD from the ISC catalogue is irregular in shape, it falls within the variability of the 20x 500-year RSQSim subsamples for magnitudes $M_w \geq 6.0$ (Fig. 2b). The annual rate of $M_w \geq 6.0$, 7.0 and 8.0 MHT earthquakes in the instrumental and historical record is also within the 16th and 84th percentiles of the 500-year RSQSim catalogue subsamples' $M_w \geq 6.0$, 7.0 and 8.0 annual rates (Fig. 2c, d and e). Between M_w 5.5-6, however, the MHT RSQSim catalogue has higher rates than the ISC catalogue (Fig. 2b). The range of $M_w \geq 7.5$ events in the 500-year-long RSQSim catalogue samples and MFD shape also aligns with the historical record of MHT seismicity (Fig. 2b). The largest event in the historical catalogue reaches M_w 8.7, while the RSQSim catalogue produces two events up to M_w 8.9 during its 15,000-year simulation time.

5.2 Spatial comparison of the MHT RSQSim catalogue with historical and instrumental seismicity

In Figure 3, we compare the spatial distribution of $M_w \geq 6.0$ earthquakes in a 5,000 year sample of the MHT RSQSim catalogue to instrumental seismicity ($M_w \geq 5.5$, white stars) since 1950. Here, the rupture area of $M_w \geq 7.5$ MHT events were constrained from the extent of damage patterns in historical documents and paleoseismic records (Bilham, 2019). The majority of events in the instrumental catalogue are below $M_w < 7.0$. However, this record does include the M_w 7.8, 2015 Gorkha earthquake (Fig. 3), which occurred at the downdip edge of MHT (depth ~ 15 km) (corresponding to the locked zone defined in the model) and did not rupture to the surface (Elliott et al., 2016). Figure 3 shows that many instrumental earthquakes nucleated

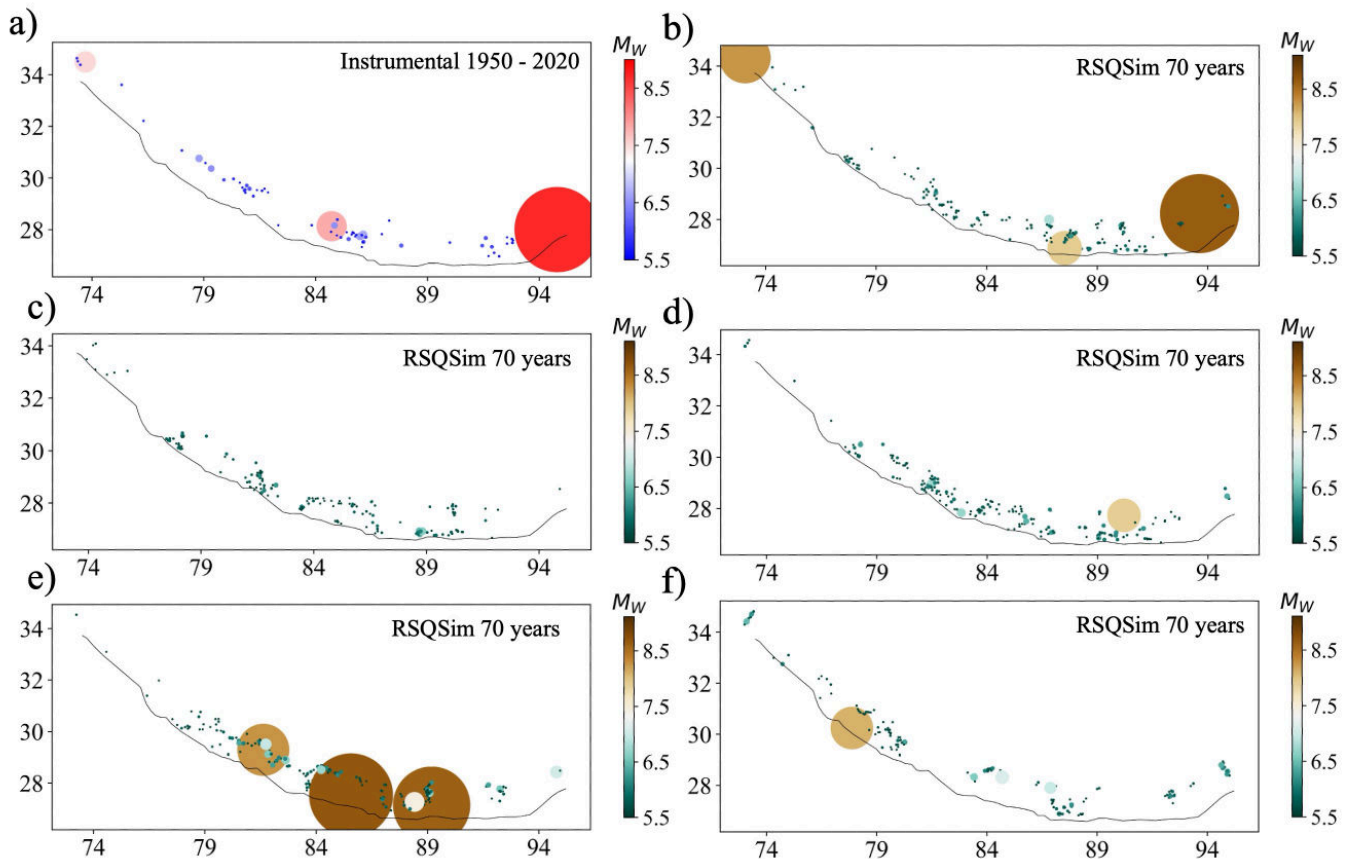


Figure 4 Comparison of synthetic earthquakes from the MHT RSQSim model with instrumental seismicity on the MHT. (a) Instrumental seismicity from 1950-2020, $M_w \geq 5.5$. (b) – (f) Synthetic earthquakes from RSQSim for five subsequent 70 years beginning from 5000-year simulations. The colour and size are coded by magnitude size. Instrumental earthquakes are taken from the International Seismological Centre (ISC) catalogue (Di Giacomo et al., 2015).

in the transition zones while significant historical earthquakes ruptured the highly coupled zone (coupling ≥ 0.5). These observations are consistent with the RSQSim catalogue, in which most $M_w < 7.0$ earthquakes nucleate in the transition zone and $M_w \geq 7.5$ in the locked zone, where there is a high accumulation of stress (Fig. 3 and Fig. 5).

In addition, we find that the spatial distribution of events within 70-year subsamples from the MHTs RSQSim catalogue, can qualitatively reproduce what was observed in MHT instrumental records between 1950-2020 (Fig. 4). For example, large events at $\sim 72^\circ\text{E}$ and 96°E longitudes in the instrumental catalogue (Fig. 4a) are replicated in Figure 4b. Likewise, there are few events at 75°E longitude in both instrumental records and the synthetic catalogue. We also analysed seismicity for other 70-year subsets, the seismicity rates varies widely, this can be explicitly observed in the MFDs (Fig. 2b). This analysis also highlights how over a 70-year time window, there is considerable variability in the rate and spatial distribution of MHT seismicity (Fig. 4b-f).

To compare the spatial distribution of events in the MHT RSQSim catalogue to the historical record of $M_w \geq 7.5$ MHT earthquakes (Bilham, 2019), we selected 10x 500-year windows of $M_w \geq 7.5$ synthetic earthquakes and plot these with the extent of the historical events. In doing so, we note that the MHT is interpreted to have

four highly coupled zones (Dal Zilio et al., 2020), which we name here from west to east as Zone 1 to Zone 4 (Table 2). From Figure 5, it can be inferred that both historical earthquakes and events $M_w \geq 7.5$ in the RSQSim catalogue have occurred in the region of highly coupled zones (coupling factor ≥ 0.5). Furthermore, the rate of $M_w \geq 7.5$ earthquakes in the RSQSim catalogue 500-year subsamples is generally comparable to the observed rates within these zones (Table 2).

In Zone 4, however, the RSQSim catalogue indicates high rates of $M_w \geq 7.5$ relative to the historical record (Table 2). There are several non-mutually exclusive factors that may account for this discrepancy: (1) the 500-year observed record is not a representative sample for the rate of $M_w \geq 7.5$ earthquakes on this section of the MHT (2) incorrectly modelled slip rates, (3) the heterogeneous pattern of high and low coupled zones that are endemic to Zone 4 and have a strong influence on the extent of ruptures in the RSQSim catalogue (Fig. 5), and (4) the ramp-thrust geometry on this section of the MHT (Elliott et al., 2016) is not incorporated into RSQSim.

To further examine $M_w \geq 7.5$ earthquakes in the MHT RSQSim catalogue, we searched for events from this catalogue that qualitatively replicate the rupture area and magnitude of nine historical ($M_w \geq 7.5$) MHT events that have occurred since 1500 CE, and for which the rupture area could be estimated based on the spatial extent of damage (Bilham, 2019; Fig. 6). In doing

Highly coupled zone from west to east (coupling factor ≥ 0.5)	Historical events $\geq M_w 7.5$ since 1500 CE	Range of the number of RSQSim events $\geq M_w 7.5$ in 10×500 years sub-catalogue	Minimum, maximum and mean RI; and CV for RSQSim events $M_w > 8.0$
Zone 1 (Lon 72°N to 77.5°N)	$M_w 7.8 \pm 0.2$ (1505) $M_w 7.8$ (1905) $M_w 7.6$ (2005)	0 – 3	~133 days, ~1600 years, ~450 years, 0.7
Zone 2 (Lon 78°N to 82.75°N)	$M_w 7.8 \pm 0.2$ (1803) $M_w 8.8 \pm 0.1$ (1505)	2 – 4	~127 days, ~500 years, ~190 years, 0.7
Zone 3 (Lon 83.5°N to 87°N)	$M_w 7.8$ (1833) $M_w 8.4$ (1934) $M_w 7.8$ (2015)	1 – 3	~30 years, ~600 years, ~550 years, 0.2
Zone 4 (Lon 87.5°N to 95°N)	$M_w 8 \pm 0.1$ (1714) $M_w 7.7$ (1947) $M_w 8.7$ (1950)	3 – 8	~10 years, ~1200 years, ~230 years, 0.9

Table 2 Comparison of the number of RSQSim events ($M_w \geq 7.5$) with historical events in each of the four highly coupled MHT zones. The recurrence interval (RI) and coefficient of variation (CV) of ($M_w > 8.0$) surface rupturing RSQSim events in these zones is also reported. A plot showing the RI distribution for these four highly coupled zones is provided in the supplementary file (Fig. S4).

so, we highlight that the purpose of this analysis is not to show that RSQSim can exactly reproduce the last 500 years of MHT seismicity, as the simulated events have occurred in a different time series, but to show that RSQSim can generate ruptures with magnitudes and extents that are close to individual historical ruptures. Of these nine historical events, five were on blind thrusts, 3 ruptured to the surface, and there is one event where the evidence for surface rupture is equivocal ($M_w 8.4$, 1934 Bihar-Nepal earthquake; Sapkota et al., 2012; Wesnousky et al., 2018).

It can be observed that RSQSim has generated events that closely approximate the ruptures areas of historical MHT earthquakes, such as the $M_w 8.8$ and $M_w 7.8$ earthquakes in 1505 and 1905 respectively (Fig. 6). However, for events around the $M_w 8.4$ (1934) and $M 8.0$ (1714) earthquakes, RSQSim simulates events with larger magnitudes and rupture areas. In the region of the 2015 $M_w 7.8$ Gorkha Earthquake, the simulated events are $< M_w 7.3$.

5.3 Maximum magnitude and extent of MHT ruptures

A key question about the MHT is whether it can host $M_w \geq 9.0$ earthquakes (e.g., Ader et al., 2012; Stevens and Avouac, 2016; Bilham, 2019; Michel et al., 2021). Based on the seismic moment deficit and recent instrumental earthquake catalogue, Stevens and Avouac (2016) argue that MHT can host millenary $M_w > 9.0$. The MHT's large area and ~11 m coseismic displacements are also consistent with $M_w > 9.0$ events (Wesnousky et al., 2017). By contrast, it is conceivable that the MHT's along-strike creeping zones (Dal Zilio et al., 2020) act as rupture barrier which limit MHT ruptures to $M_w < 8.7$ events (Michel et al., 2021). Alternatively,

Bilham (2019) estimated the maximum potential magnitude for future earthquakes on the MHT by dividing it along-strike into 15 segments and then assigning a magnitude to each segment based on the slip accumulated since its last rupture. From this segmented model, Bilham (2019) estimated $M_w 7.8$ - 8.7 (Fig. 7a).

In the MHT-RSQSim catalogue, we find that the maximum event magnitude is $M_w \leq 8.9$ (Fig. 7). However, we also found that the upper limit of MHT seismicity varies along strike, with coupled Zones 2 and 3 limited to $M_w \leq 8.5$ events (Fig. 7a). From comparing the along-strike extent of MHT $M_w > 8.0$ ruptures in the RSQSim catalogue, it can be seen that the low coupling zones along the MHT act as rupture barriers. The RSQSim catalogue is broadly similar to the maximum magnitude estimates from Bilham (2019) except on the MHT's weakly coupled zones where RSQSim indicates lower magnitude events (Fig. 7a).

Despite implementing a planar MHT geometry in RSQSim, it only simulates surface ruptures in events $M_w > 8.0$ within highly coupled zones. The mean recurrence interval of these events are 200-600 years. In addition, we find that these event's recurrence interval coefficient of variation (CV = mean recurrence interval/recurrence interval standard deviation) implies periodic surface ruptures in Zone 3 (CV = 0.2) and weakly periodic ruptures in Zones 1, 2, and 4 (CV = 0.7-0.9, Table 2).

Since a $M_w \sim 8.8$ earthquake in 1505 CE, there have been no surface-rupturing earthquakes in Zone 2 (Bilham, 2019). From evaluating the RSQSim catalogue, we found that such a long recurrence interval for $M_w > 8.0$ ruptures on this MHT section is possible in two cases: (1), from $M_w \sim 8.5$ events that rupture the entirety of Zone 2, and which require ≥ 480 years of slip accumulation to produce the next $M_w > 8.0$ rupture, and (2) when

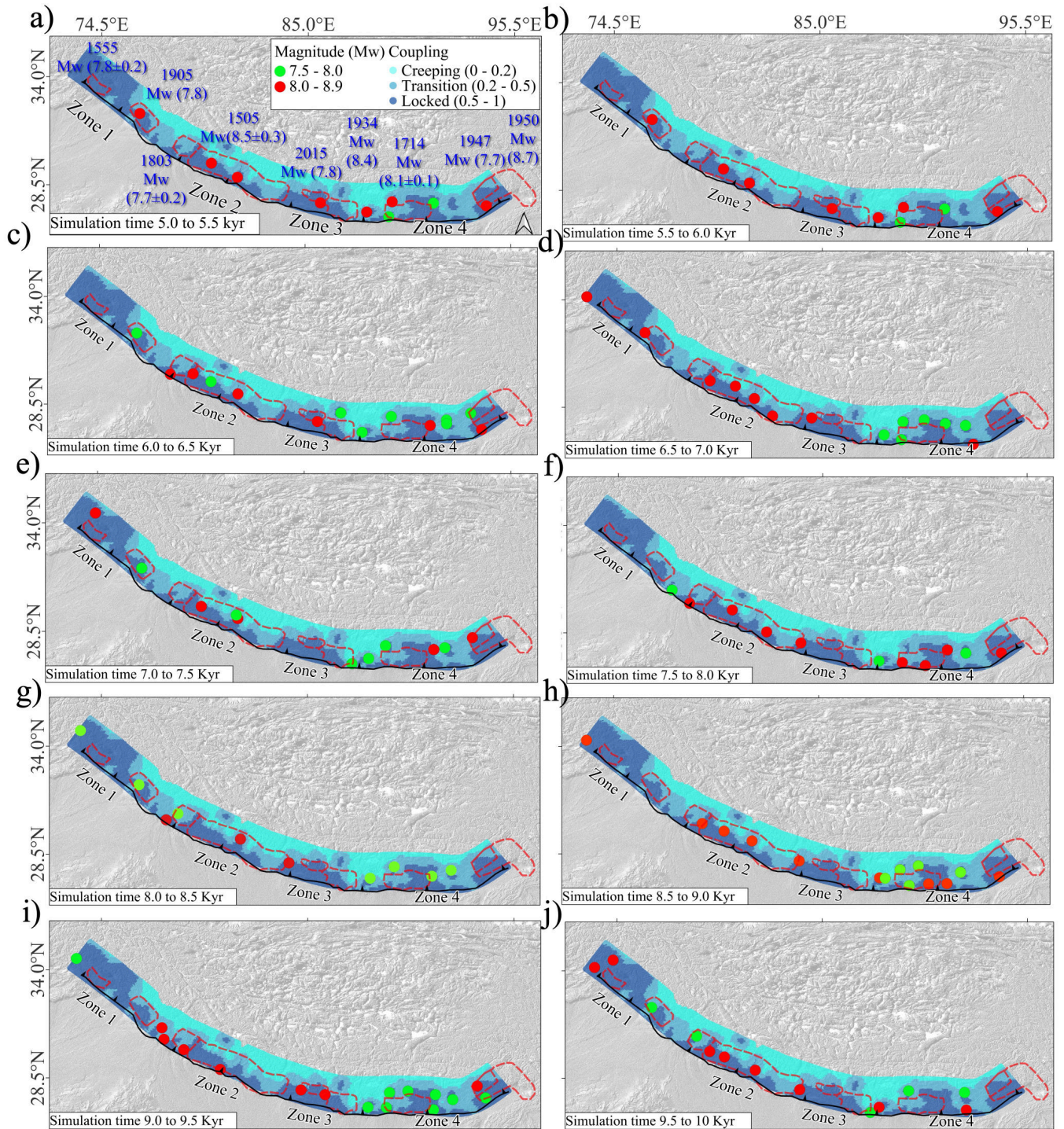


Figure 5 (a)-(j) Epicentre of $M_w \geq 7.5$ events in successive 500 year samples of the MHT RSQSim catalogue (green and red dots) plotted with the area of historical ruptures (red dashed area) and its magnitude (blue color text) since 1500 CE (Bilham, 2019) and the coupling factor (Dal Zilio et al., 2020).

there is an event that only partially ruptures Zone 2, and it is followed by a subsequent event within a very short period (about four months) that ruptures the remaining area (see Fig. S5 for ruptures within 4 months in zone 2), and after which there is a ~ 500 year long period of quiescence. Historical and paleoseismic evidence revealed that following a major surface rupture in Zone 3 in 1255 CE, there was not another major rupture until 1934 (Sapkota et al., 2012). This is consistent with the recurrence interval of surface rupturing $M_w > 8.0$ earthquake on this zone in the RSQSim catalogue (mean and

standard deviation 550 ± 150 years).

6 Implications for seismic hazard

6.1 Hazard estimates from MHT RSQSim catalogue

We now describe PSH maps that are derived from the MHT RSQSim catalogue and compare them with a conventional seismic hazard model for this region (Stevens et al., 2018). To estimate seismic hazards using synthetic

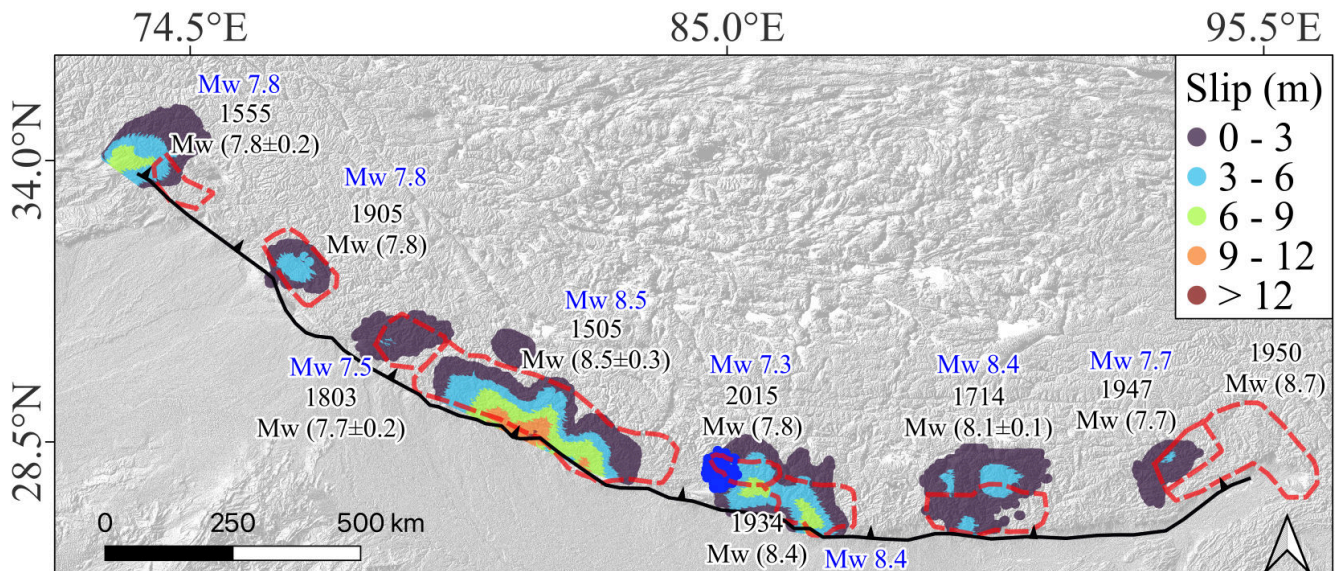


Figure 6 Historical ruptures on the MHT since 1500 CE (red dashed polygons; Bilham, 2019) and events from the MHT RSQSim catalogue that we interpret to be close approximations of these events based on their rupture extent and magnitude. The black solid line shows the MHT surface traces. The blue text shows the RSQSim magnitude, and the black text shows the year and magnitude of historical events.

earthquakes from the MHT RSQSim model, we adopted the approach performed by Shaw et al. (2018) for evaluating a California-based RSQSim catalogue. Each event in the RSQSim catalogue is treated as an independent source, with an occurrence rate equal to the inverse of the catalogue duration. Ground motions are stochastically simulated at each site using magnitude, rupture distance (R_{rup}), average shear wave velocity to 30 m (V_{s30}), and other parameters required by ground motion models (GMMs). The resulting ground motions are ranked in descending order, and values corresponding to specific return periods/probabilities of exceedance (PoE) are selected (Musson, 1999; Shaw et al., 2018; Williams et al., 2023). Previous studies have suggested that the MHT should be treated as a crustal subduction zone source (Thingbaijam et al., 2017; Stevens et al., 2018), and so we calculate peak ground acceleration (PGA) ground motions using the recently developed subduction zone GMMs by Parker et al. (2020) and Abrahamson and Gulerce (2022). V_{s30} values are taken from the USGS Global V_{s30} Mosaic (Allen and Wald, 2007).

PGA estimates for three PoE are shown in Figure 8a–c. Generally, a ground motion with a 10% PoE in 50 years is used to estimate earthquake loads on standard infrastructure, 2% PoE in 50 years for critical infrastructure such as hospitals and major bridges, and 0.5% PoE in 50 years applies to large dams. This latter point is particularly relevant due to the ongoing expansion of hydroelectric infrastructure in the Himalayas (Gautam et al., 2014). At 10% PoE in 50 years, we estimated $\sim 1g$ as the maximum PGA (Fig. 8a). Except for central Nepal and the western Himalayas, most areas above the MHT exhibit PGAs around 0.7g. At 2% and 0.5% PoE in 50 years, maximum PGAs reach approximately 2g (Fig. 8b) and 3g (Fig. 8c), with relatively uniform distribution across the Himalayas. However, in the western section of the

Himalayas, PGAs are relatively low compared to other sections. As expected, PGAs attenuate with increasing distance from the MHT.

6.2 Comparison of MHT RSQSim catalogue-derived hazard with the classical seismic hazard in Nepal

To compare the RSQSim-based seismic hazard estimates with a classical PSHA approach (Cornell, 1968), we consider the PSHA performed for Nepal by Stevens et al. (2018). We retained the MHT source model and recurrence parameters from Stevens et al. (2018), but applied the GMMs (Parker et al., 2020; Abrahamson and Gulerce, 2022) and V_{s30} condition used in our RSQSim analysis. This ensures that differences in hazard arise solely from the source models. The sites in both models were spaced at 0.1×0.1 degrees in longitude and latitude. We chose to compare the MHT RSQSim catalogue-derived hazards with the Stevens et al. (2018) source model because it is the only PSHA model in the Himalayas that treats the MHT as a single source.

In the Stevens et al. (2018), the MHT has a maximum magnitude of $M_w 9.2 \pm 0.2$ with a recurrence interval of ~ 1000 years and is modelled using the Gutenberg-Richter relationship with a and b -values of 6 ± 0.2 and 1 ± 0.025 , respectively. Their adoption of the MHT is slightly different from that used in the MHT RSQSim catalogue since (1) its seismicity rates are based on a different coupling model (Stevens and Avouac, 2015, 2016), and (2) they adopted the ramp-flat-ramp MHT geometry. This MHT geometry is also adopted by the National Building Code of Nepal (NBC) 2020 PSHA (Chamlagain et al., 2020). All other seismic sources in Nepal that are considered by Stevens et al. (2018) were removed in this MHT hazard comparison.

Fig. 9 and Fig. 10 show the hazard comparison at 10%,

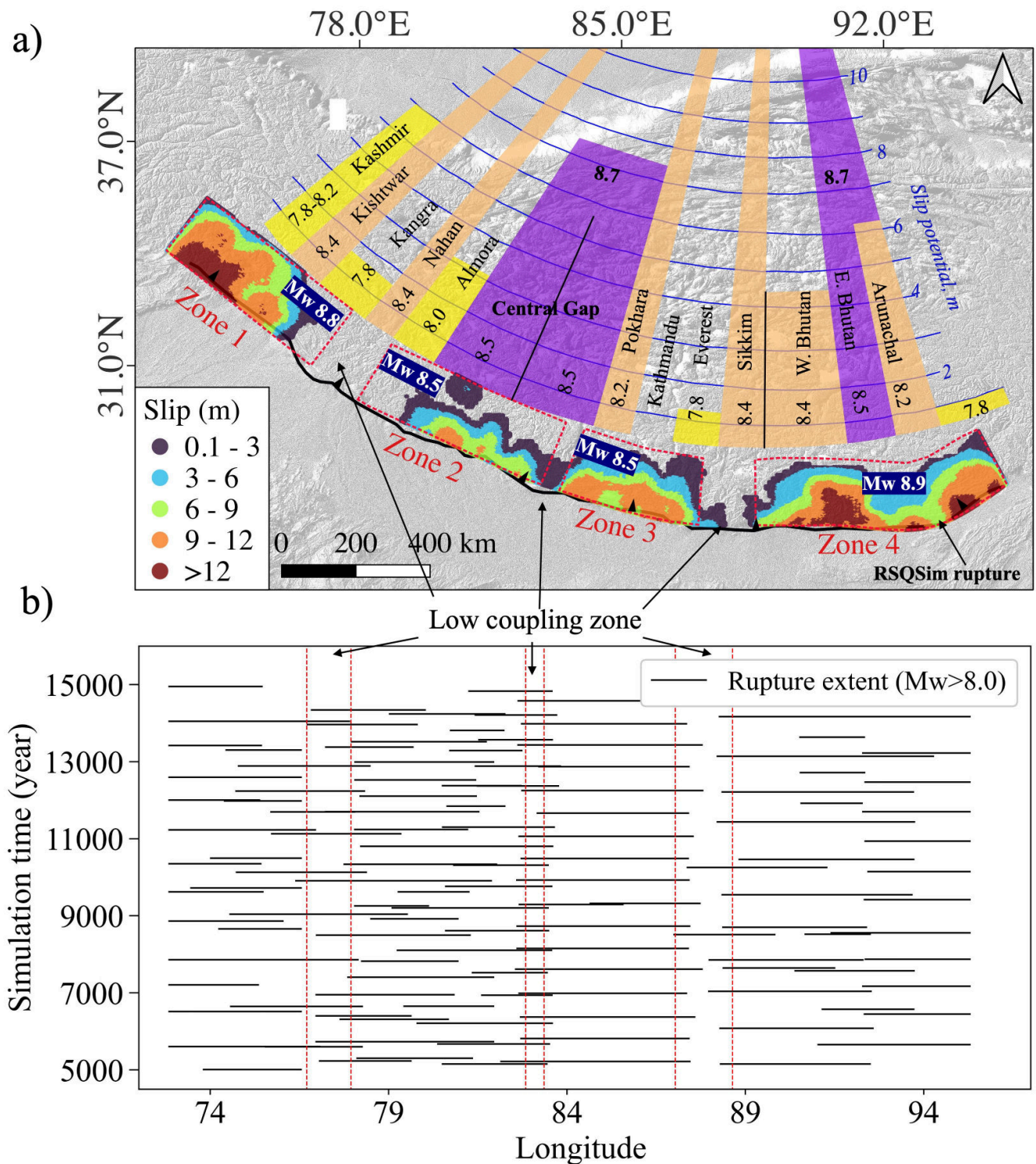


Figure 7 (a) Rupture extent of the maximum magnitude event in the MHT RSQSim catalogue for Zones 1-4. The purple, brown, and yellow shading shows the magnitude and slip potential (m) on the MHT segment since the last events (after Bilham, 2019). (b) E-W rupture extent for surface rupturing $M_w > 8.0$ earthquake over the entire 10,000 years duration RSQSim catalogue. Vertical dotted red lines indicate the boundary between the high and low coupled zones.

2% and 0.5% PoE in 50-year PGAs for the sites within Nepal. Overall, the RSQSim-derived and classical seismic hazard maps exhibit similar spatial patterns, with elevated hazard levels above the MHT. However, we find that the hazard estimates from the classical model are generally higher than obtained from the RSQSim Catalog (Fig. 9 & Fig. 10). At 10% PoE in 50 years the hazard differences (MHT RSQSim catalogue derived – classical)

range from +0.1g to -0.6g (Fig. 9c), or in terms of % with respect to classical hazard, from +20% to -70% (Fig. 9d). At 2% PoE, the differences are from +0.3g to -0.6g, which corresponds to +30% to -40% with respect to classical hazard (Fig. 9g & Fig. 9h), and +0.4g (+30%) to -0.7g (-40%) at 0.5% PoE in 50 years (Fig. 9k & Fig. 9l). In relative terms, this means that the discrepancies are largest at 10% PoE in 50 years level, where for 84% of sites, the

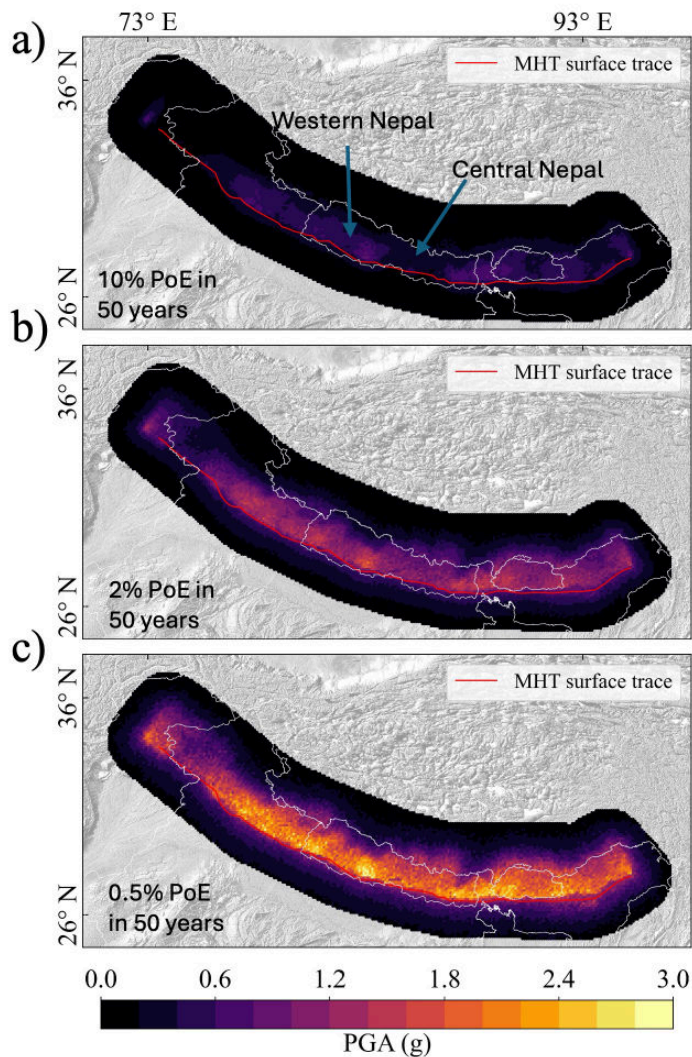


Figure 8 Peak ground acceleration at (a) 10% PoE, (b) 2% PoE, and (c) 0.5% PoE in 50 years return period prepared using 10,000 year sample ($5.5 \leq M_w \leq 8.9$) of the MHT RSQSim catalogue.

RSQSim derived hazard differs by 60% from the classical model (Fig. 10d & Fig. S6d), while at 2% & 10% PoE in 50 years, 84 % of sites have absolute hazard difference below 30% (Fig. 10d). Hazard estimates from the classical method are particularly high in the high coupling zones with the most significant differences between 83.5° and 86.5° longitudes (Zone 3).

7 Discussion

Overall, we suggest that the 10,000-year RSQSim catalogue for the MHT captures the range of historical and, to a lesser extent, instrumental seismicity observed in the Himalayas (Fig. 3). In particular, RSQSim is able to replicate that smaller events on the MHT tend to nucleate in the transition zones, and larger events ($M_w \geq 7.5$) in the highly coupled zones, i.e. in the regions of high-stress concentration (Figs. 3 and 6; Bilham, 2019). Indeed, there are events in the RSQSim catalogue whose magnitude and spatial extent are remarkably similar to historical MHT events (e.g. the 1505 M_w 8.8 earthquake, Fig 6).

In detail, the rupture area of some historical earthquakes, such as the 1934 M_w 8.4 Bihar-Nepal and 1714 M_w 8.0 Bhutan earthquakes are smaller than an equivalent ruptures in the RSQSim catalogue. This might be because of the following reasons. Firstly, since the rupture area of historical earthquakes are constrained through reports of damage, they could be underestimated if they extended into unpopulated regions. Second, based on a palaeo-seismological study and geomorphological mapping, Sapkota et al. (2012), suggested that the Bihar-Nepal 1934 rupture area could be more extensive than previously thought (Fig. 5 in Sapkota et al., 2012). Finally, it has been proposed that a thrust ramp at ~ 10 km depth controls the rupture extent in the eastern MHT (Elliott et al., 2016; Hubbard et al., 2016; Dal Zilio et al., 2020; Sathiakumar and Barbot, 2021). By contrast, we adopted a planar MHT geometry in our RSQSim model for consistency with the coupling model (Dal Zilio et al., 2020). We did perform RSQSim simulations with a non-planar MHT geometry, however, this resulted in catalogs with an excessive number of small-moderate magnitude events that terminated at the ramp and flat intersections, and so did not agree with historical MHT earthquakes (Fig. S7). Hence future efforts should be directed towards developing geometric models that allow RSQSim to correctly incorporate the eastern MHT's thrust ramp geometry (e.g., Howell et al., 2025).

Other discrepancies also exist between observed and RSQSim MHT seismicity, and these likely reflect simplification of earthquake physics in RSQSim, characteristics of the Dal Zilio et al. (2020) coupling model, and the approach used for earthquake magnitude assignment. For example, RSQSim generates a relatively higher number of M_w 5-6 events along the MHT compared to the ISC catalog (Fig. 2b). This could represent that the ISC catalog is incomplete for events this magnitude range and/or the tendency for RSQSim to generate high stress drop single or two patch events (Liao et al., 2024; ?).

Our approach also explicitly assumes a stationary coupling pattern over a 15,000-year simulation, whereby spatial domains inferred from geodesy as creeping, transitional, or locked along the MHT are treated as persistent throughout the RSQSim runs. We acknowledge that this is a simplification, as coupling may evolve over multiple seismic cycles due to stress redistribution, variations in effective normal stress, changes in fluid pressure, or long-term rheological processes (e.g., Dresen et al., 2020; Amemoutou et al., 2023). Therefore, our approach should not be taken to mean that coupling necessarily remains permanently unchanged over thousand year timescales. Instead, we use this assumption as a practical simplification that allows us to examine how the present-day, geodetically inferred coupling pattern influences long-term rupture behaviour, while keeping the frictional properties and loading conditions consistent and stable within RSQSim. Introducing time-dependent coupling into the RSQSim model in the future may provide further insights into the rupture barrier due to the low coupling zone at present.

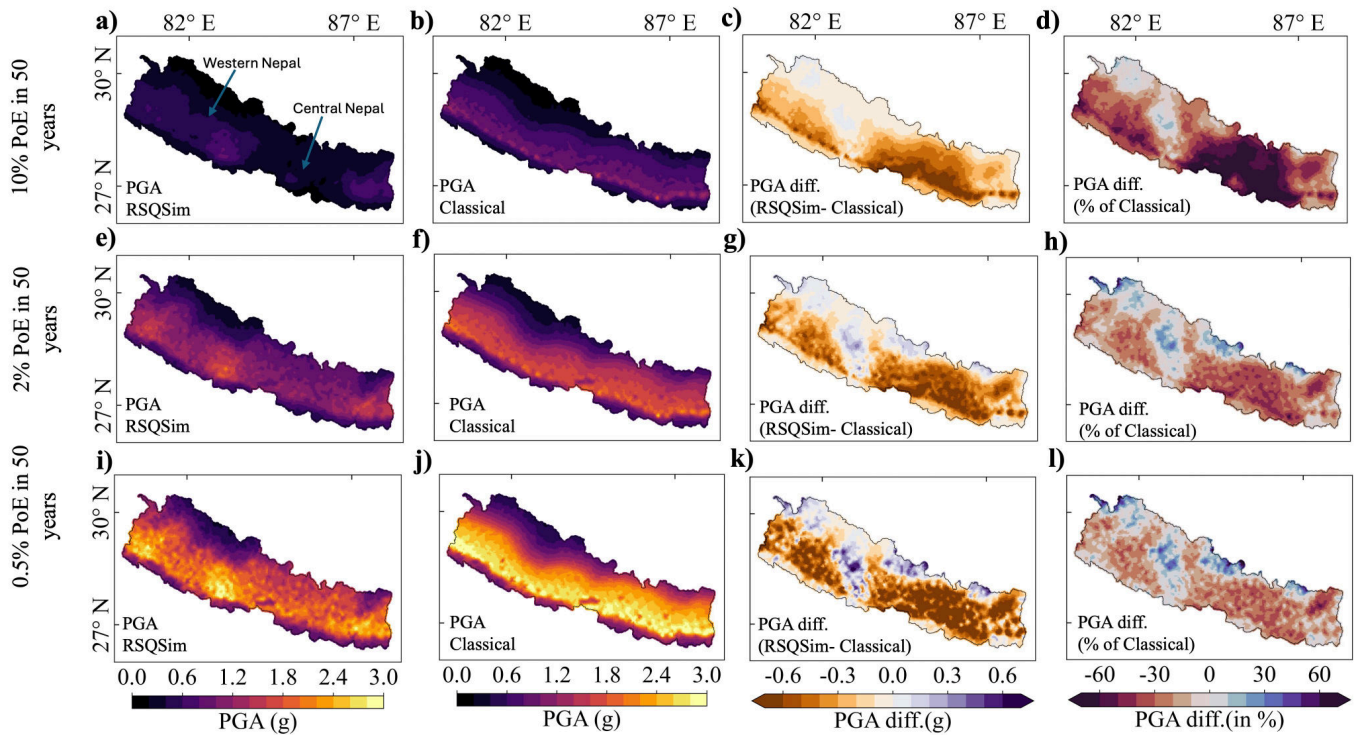


Figure 9 (a), (e) & (f) seismic hazard maps for Nepal derived from (a,e & i) the MHT RSQSim catalogue, and (b), (f) & (j) classical PSHA maps from (Stevens et al., 2018). Maps are for 10%, 2% and 0.5% PoE in 50 years. (c), (g), and (k) hazard difference between RSQSim and the classical PSHA for the same PoE. (d), (h), and (l), hazard difference between the two models once normalized by the hazard estimates from the classic model.

The overall good correspondence between observed and synthetic MHT seismicity gives us confidence that we can use emergent features from this RSQSim catalogue to provide new insights in MHT seismicity. In particular, based on the parameters we adopted, we observed that the central section of the MHT could host $M_w \sim 8.5$ earthquakes, the eastern section $M_w \sim 8.9$, and the western $M_w \sim 8.8$, with geodetically inferred low-coupling regions (50–100 km wide) between these segments acting as rupture barriers to through going MHT earthquakes (Fig. 7). Our study, therefore, supports the findings from Michel et al. (2021) that low coupling zones along the MHT prevent it from rupturing in $M_w > 9.0$ events.

We also note that Zone 3 exhibits a more regular earthquake cycle and a more consistent rupture extent than the other zones (Table 2). It has the largest area of high coupling (coupling > 0.5) and is relatively homogeneous in terms of coupling distribution. This uniform and large coupling area results in consistently high stress accumulation on the zone's patches, and its subsequent release in large-magnitude earthquakes ($M_w > 8.0$) at relatively regular intervals ($CV = 0.2$). In contrast, Zones 1, 2, and 4 have greater heterogeneity in coupling. This spatial variability leads to differences in loading and promotes irregular earthquake cycles ($CV = 0.7-0.9$) and rupture extents (Delogkos et al., 2023). Because the frictional parameters are identical across all zones, the observed differences in earthquake extent and recurrence patterns are primarily governed by variations in coupling and the associated slip deficit rates.

The hazard estimates we derived from implementing

the MHT RSQSim catalogue into a stochastic PSHA are generally lower than those from a conventional PSHA that uses the MHT source model from Stevens et al. (2018) (Fig. 9). These decreases are most significant at a 10% PoE in 50 years hazard level, and reduce at longer return periods (Figs. 9 and S5). One of the main causes of the discrepancies in PGA values is that the seismic moment deficit rate in the Stevens and Avouac (2015) coupling model is $\sim 30\%$ higher than the Dal Zilio et al. (2020) model (see supplementary file, Fig. S8).

Stevens et al. (2018) also assumed uniform earthquake rates across the MHT ($a = 6 \pm 0.2$ & $b = 1 \pm 0.025$), which has resulted in higher earthquake rates than RSQSim and recorded instrumental for $M_w \leq 7.5$ (Fig. S9). However, it has been observed that seismicity is not uniform across the MHT. For example, earthquakes $M_w \leq 7.8$ tend to cluster at the downdip edge of the MHT and produce partial ruptures, while $M_w > 8$ surface rupturing events occur only along its highly coupled zones (Pandey et al., 1995; Dal Zilio et al., 2019; Sathiakumar and Barbot, 2021). We suggest that this observed bimodal MHT seismicity is more faithfully captured by the RSQSim catalogue than the Stevens et al. (2018) model. Zone 3 exhibits the largest discrepancies in hazard estimates. In this region, the RSQSim catalogue yields a longer recurrence interval (600 years) for $M_w > 8.0$ events due to the lower slip rate prescribed by the Dal Zilio et al. (2020) coupling model—an effect not accounted for in the Stevens et al. (2018) model. These significant differences in the hazards demonstrate that physics-based simulators can more faithfully incorporate along-strike slip rate differences in fault source

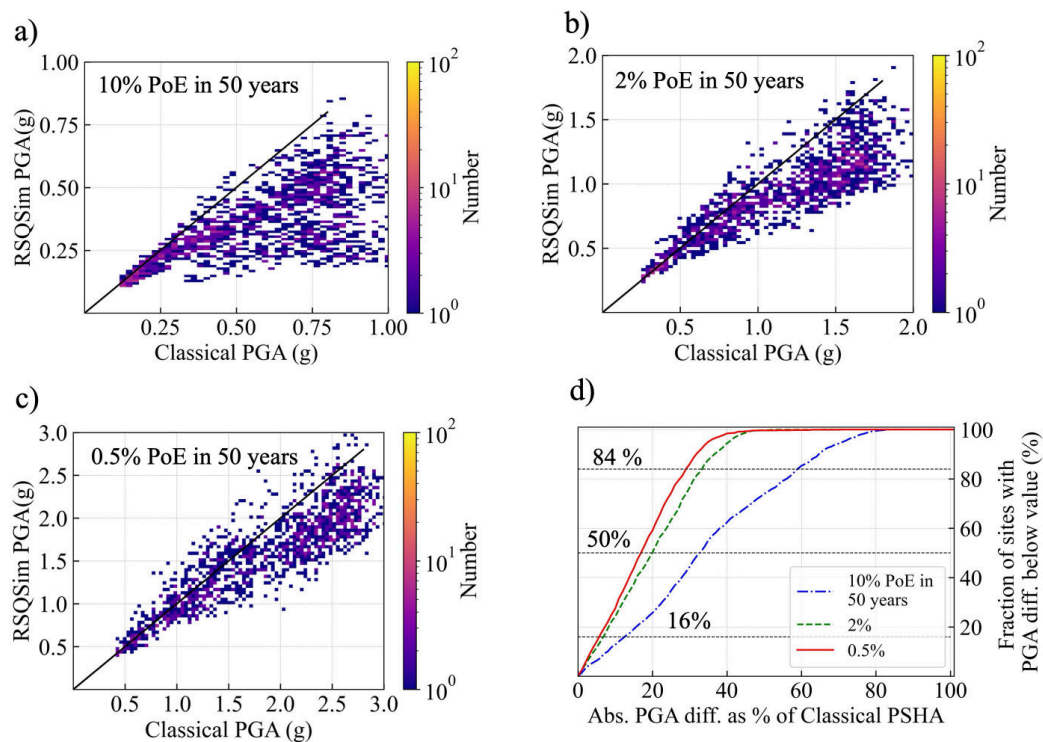


Figure 10 Site-wise comparison of hazard from MHT RSQSim catalogue with classical in Nepal for (a) 10% PoE, (b) 2% PoE, and (c) 0.5% PoE in 50 years, respectively. (d) absolute PGA difference in % with respect to classical PSHA PGAs versus the proportion of sites with PGAs difference below this value.

models than conventional PSHA.

In summary, our study highlights that RSQSim can reproduce seismicity rates, rupture extents, and scaling relations on the MHT that are similar to historical and instrumentally recorded earthquakes. As such, our study provides a foundational dataset for future studies that use paleoseismology, geodesy, historical and instrumental earthquake records, or other earthquake simulators, to evaluate MHT seismicity. In addition, our RSQSim catalog allows a rich variety of MHT rupture behaviour to be incorporated into seismic hazard assessment, and which would not otherwise be possible in conventional seismic hazard models.

8 Conclusions

Using the RSQSim earthquake simulator and previously published geometry, slip rates, and fault friction properties, we generated a 10,000-year-long physics-based earthquake catalogue for the MHT. The resulting synthetic catalogue reproduces key features of the MHT's historical and instrumental seismicity. In addition RSQSim provides new insights into the MHT's seismicity, such as the inference that along-strike low-coupling zones act as barriers to rupture propagation, limiting the maximum simulated earthquake magnitude to M_w 8.9. Hazard estimates from classical PSHA tend to be higher than those derived from the RSQSim catalogue, particularly at 10% PoE in 50 years. These findings suggest that physics-based earthquake catalogues offer a valuable complement to classical PSHA methods for assessing seismic hazard in the Himalayas.

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Data and code availability

The MHT RSQSim model, earthquake catalogues and Python code for data analysis and PSHA are available at [Niroula \(2026\)](#).

Competing interests

The authors declare that there are no competing interests.

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