# Fragility Curves from Hazard to Risk: – Tofino, British Columbia, Canada subjected to Cascadia Subduction Earthquakes –

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# Context & Outline

- A long-term multi-hazard risk assessment is essential for developing disaster risk management strategies to achieve a disaster resilient and sustainable community.
- Tofino is one of the most exposed locations in Canada to seismic-tsunami risks from the Cascadia subduction zone in the Pacific Northwest.
- This presentation summarizes a long-term multi-hazard risk assessment for Tofino in the context of '*fragility curves: from hazard to risk*'.
  - Current multi-hazard risk modeling and assessment
  - Analytical fragility curves – state-dependent fragility curves coupled simulations of shaking & tsunami load sequences
  - Fatality risks for residents and tourists (frequency-number of fatalities (*F*-*N*) curves and evacuation modeling)

# Tofino

- Located at Esowista Peninsula within Clayoquot Sound on Vancouver Island
- Natural scenery, sandy beaches, lakes, inlets, and ancient rainforests
- Exposed to the Cascadia subduction zone – earthquake and tsunami risks – possibility for *M*9 megathrust event
- Other coastal hazards (storm flooding) and sea-level rise (+1.0 m by 2100)
- Could be isolated after major events

# Tofino

- Tofino Town – consisting of commercial and residential areas – elevated areas (above 10 m)
- Beach areas – residential and camp sites/resort facilities - below 10 m

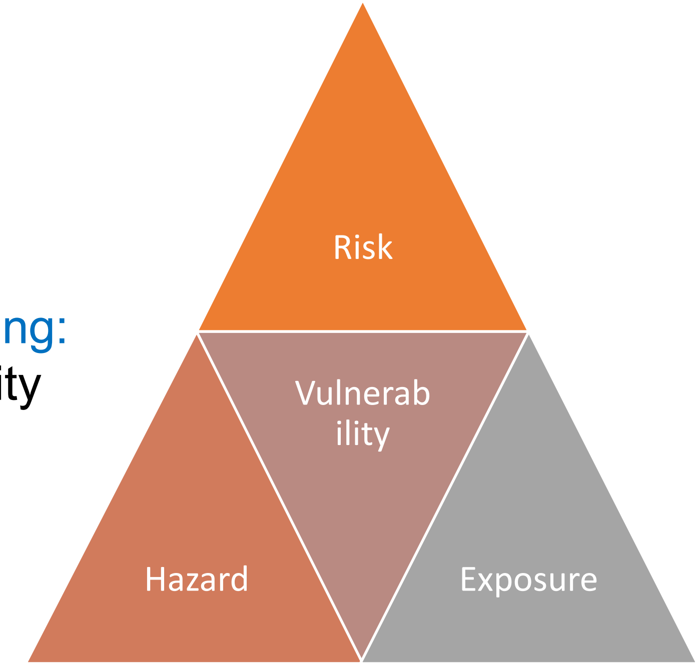


Tofino Town

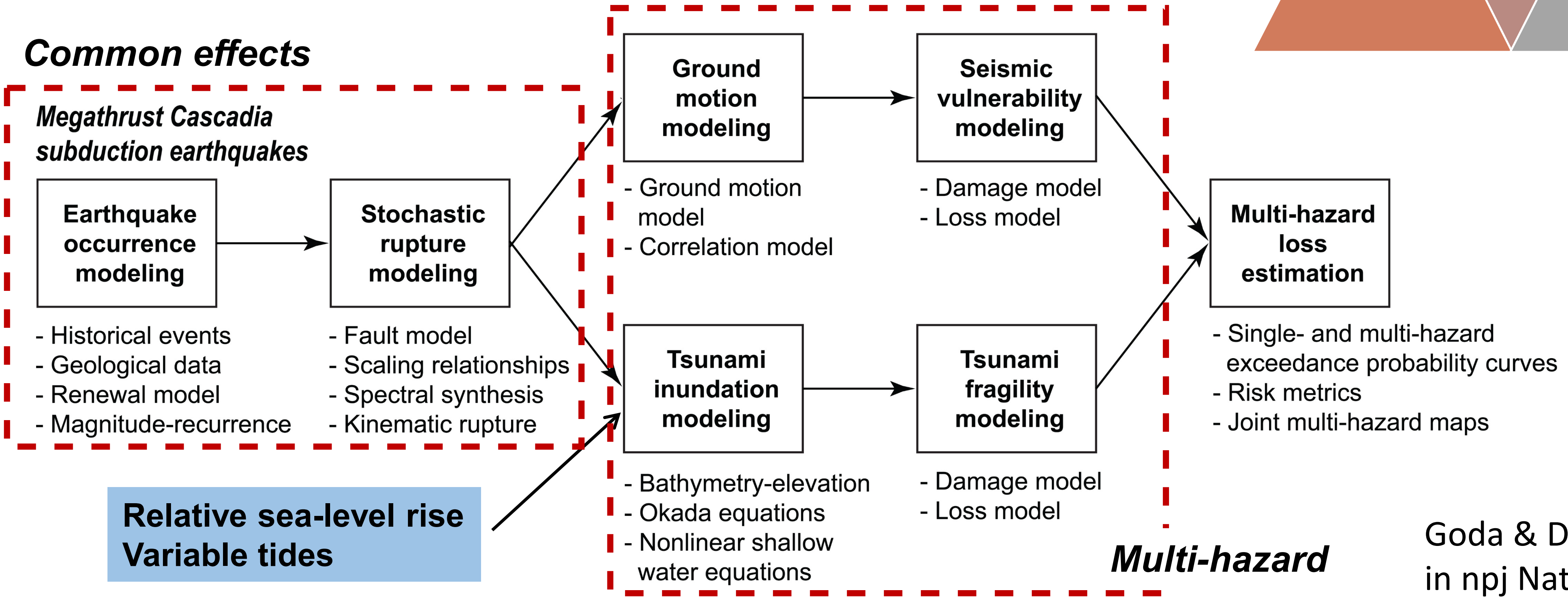

Chesterman Beach


Cox Bay

# Multi-hazard Risk Assessment for Earthquakes and Tsunamis



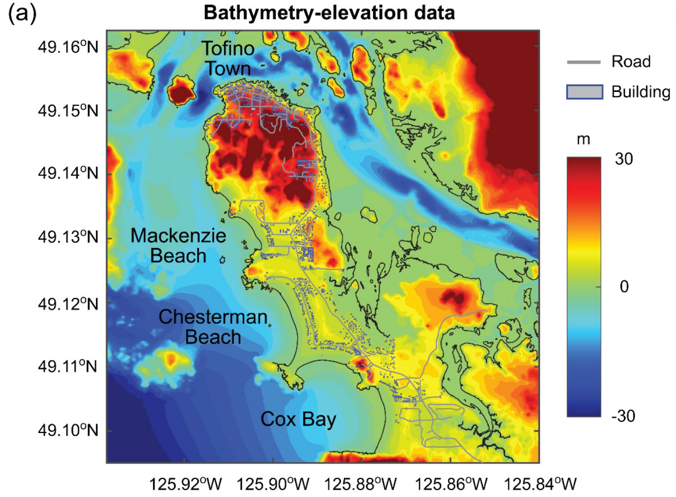

- Earthquake-tsunami catastrophe modeling:
  Risk = Hazard × Exposure × Vulnerability

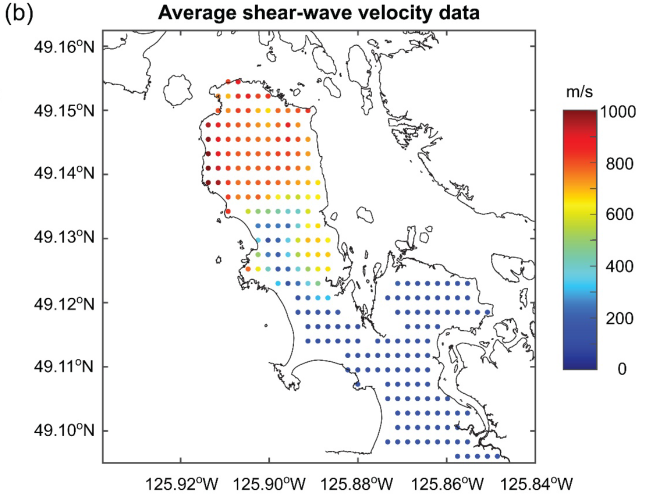


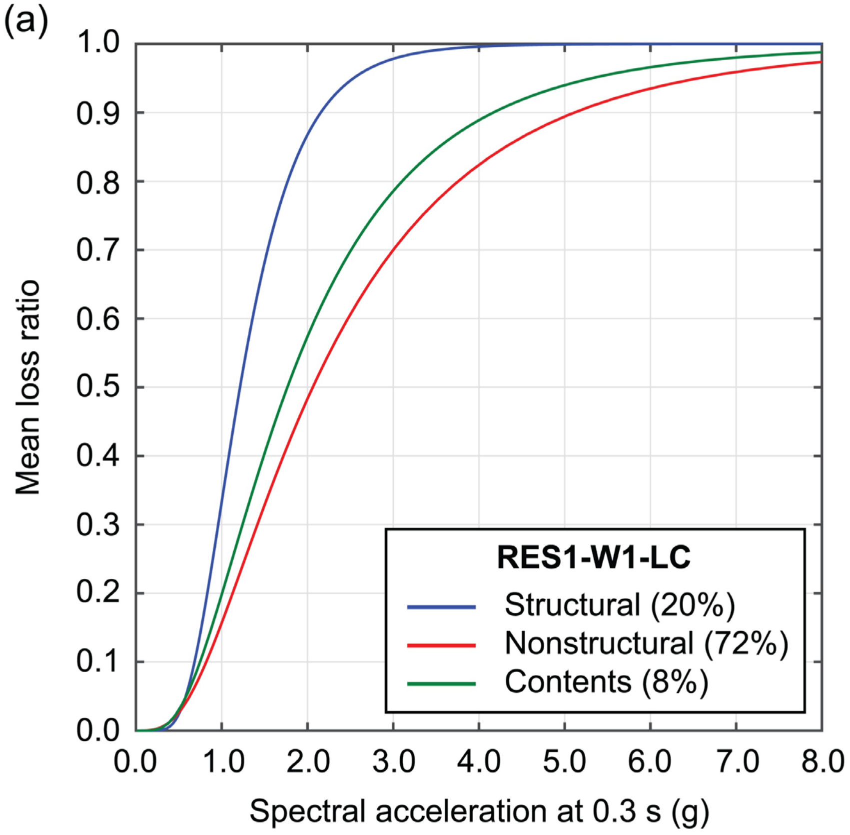

Goda & De Risi (2024) in npj Natural Hazards

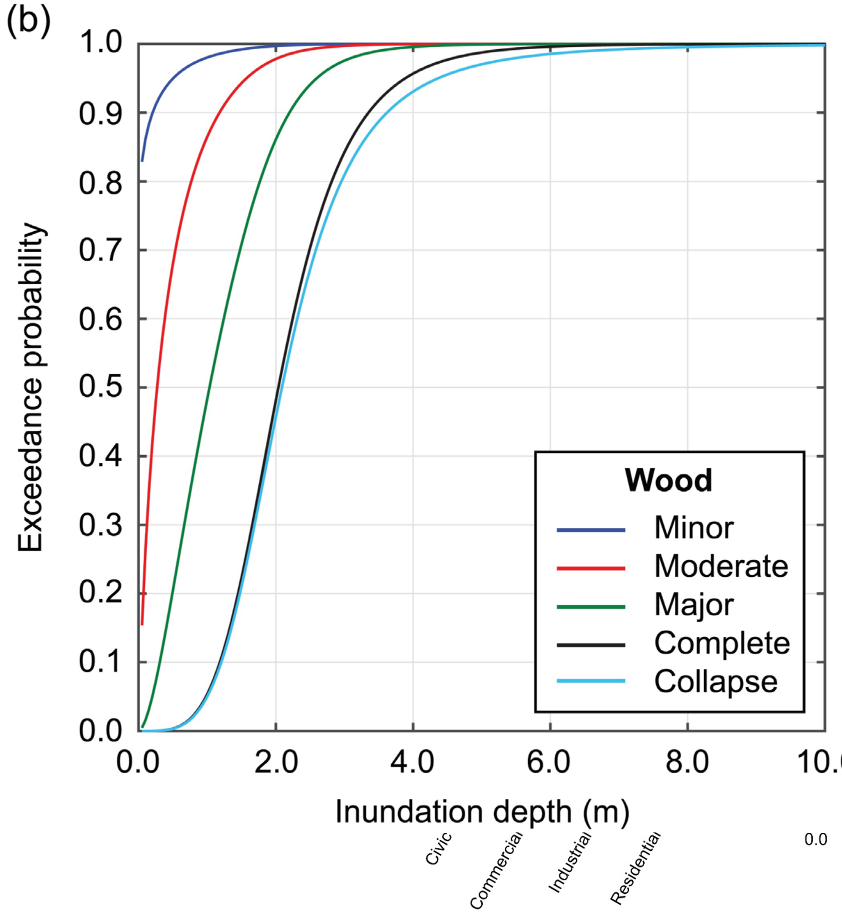
# Building Exposure & Fragility Models

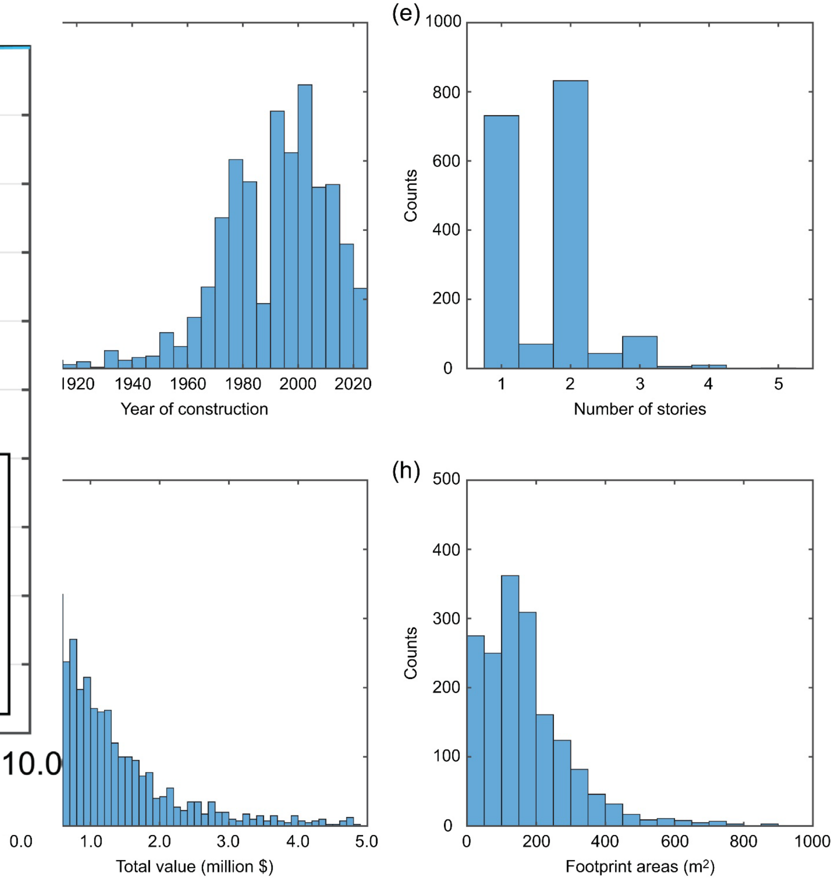
- 1789 buildings in Tofino are considered.



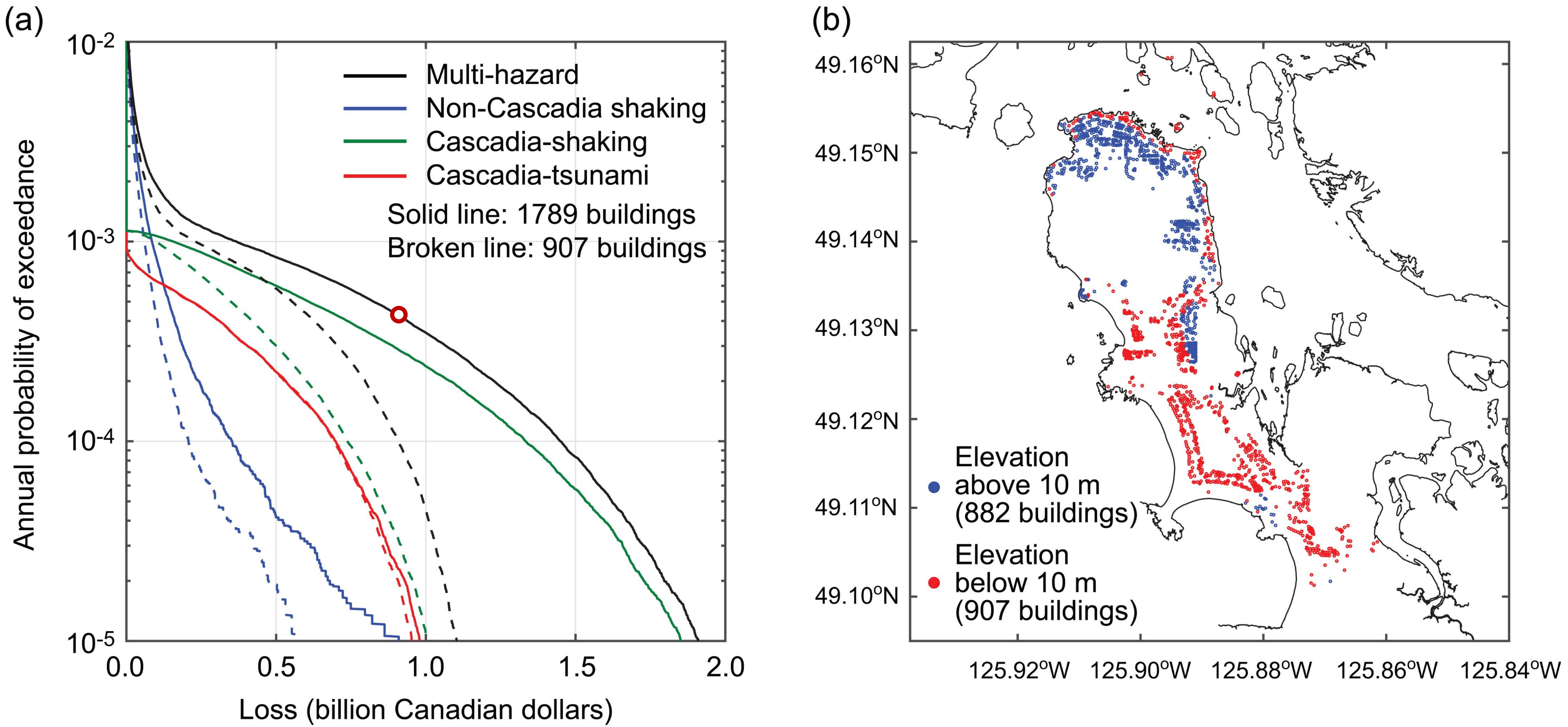



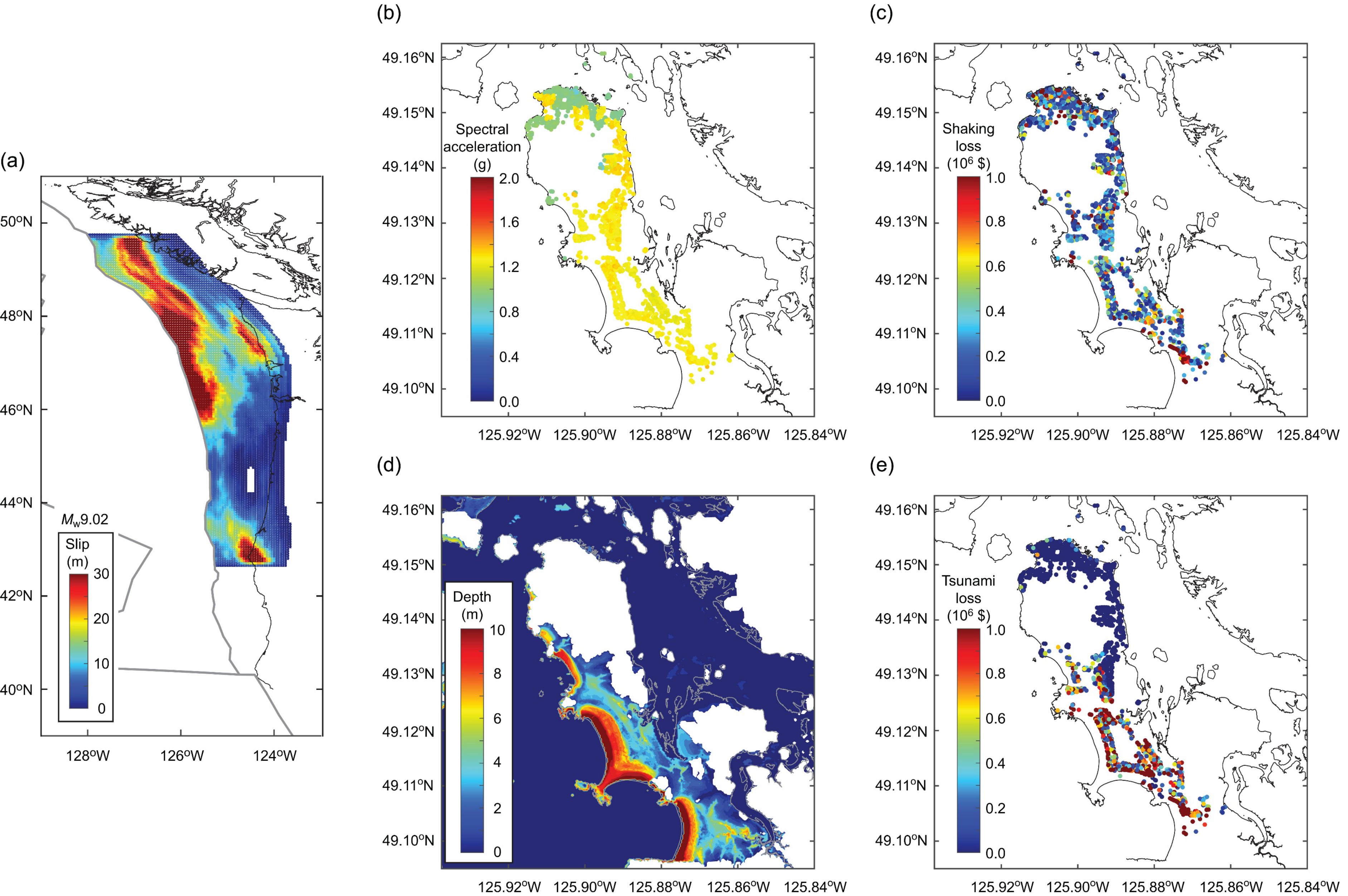



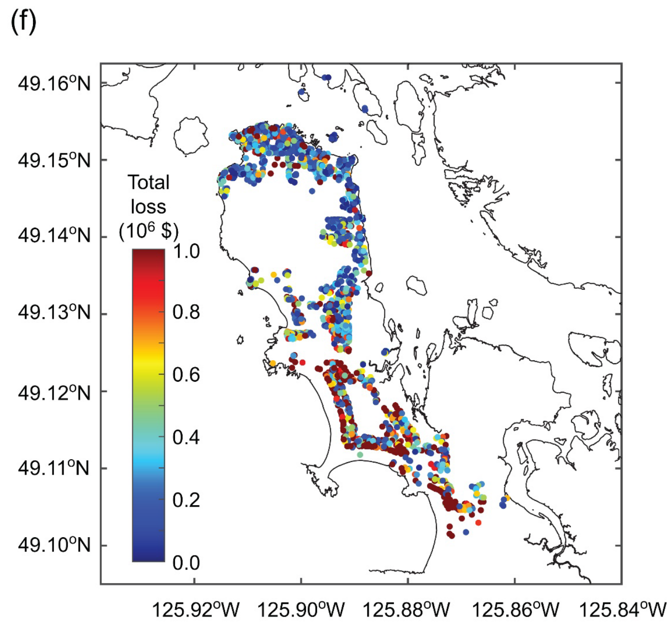
# Multi-hazard Risk Curves

- For low-lying buildings, shaking and tsunami risks are of similar magnitude.
- Local topography is important – need for multi-hazard risk-based microzonation.



# Multi-hazard Maps for Return Period of 2500 years

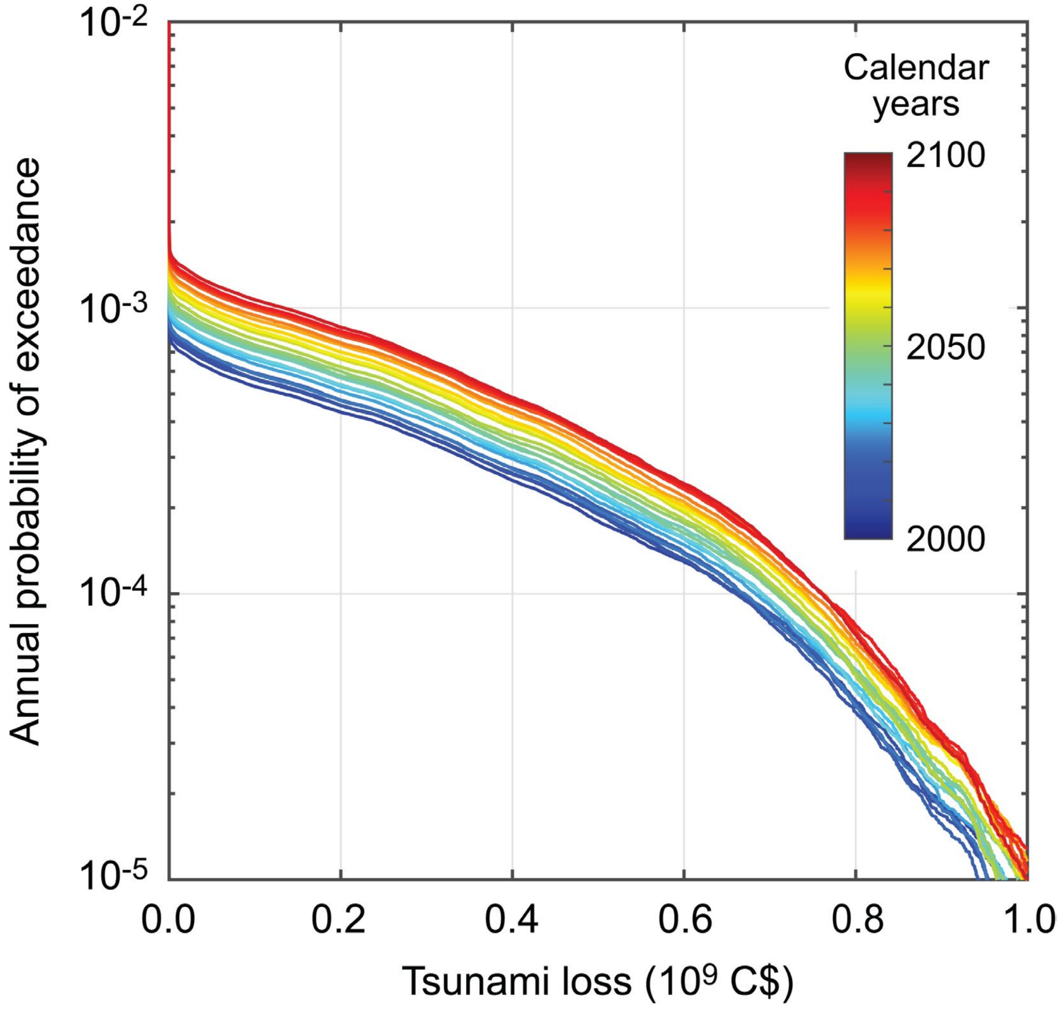



Larger loss is taken as a final multi-hazard loss per building

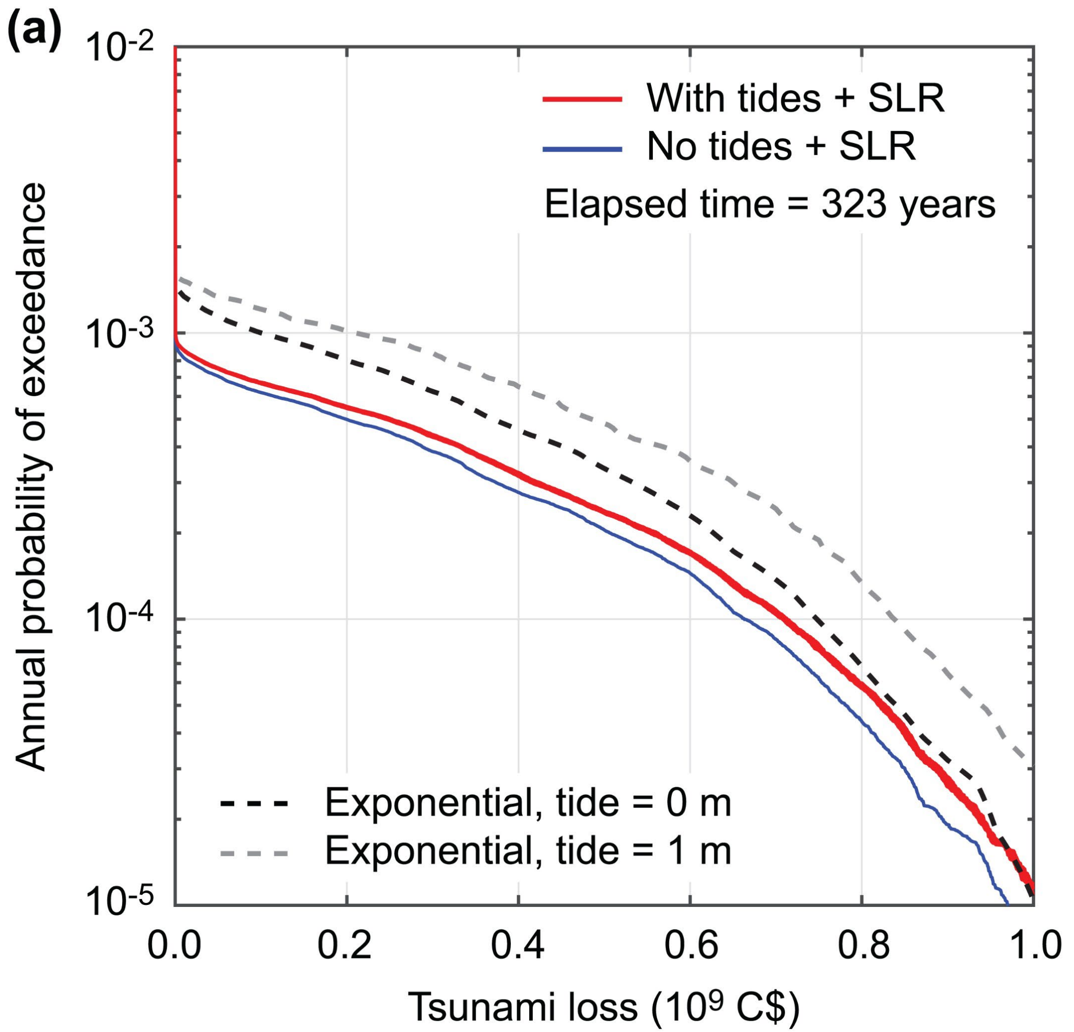
# Time-dependent Tsunami Risk Curves

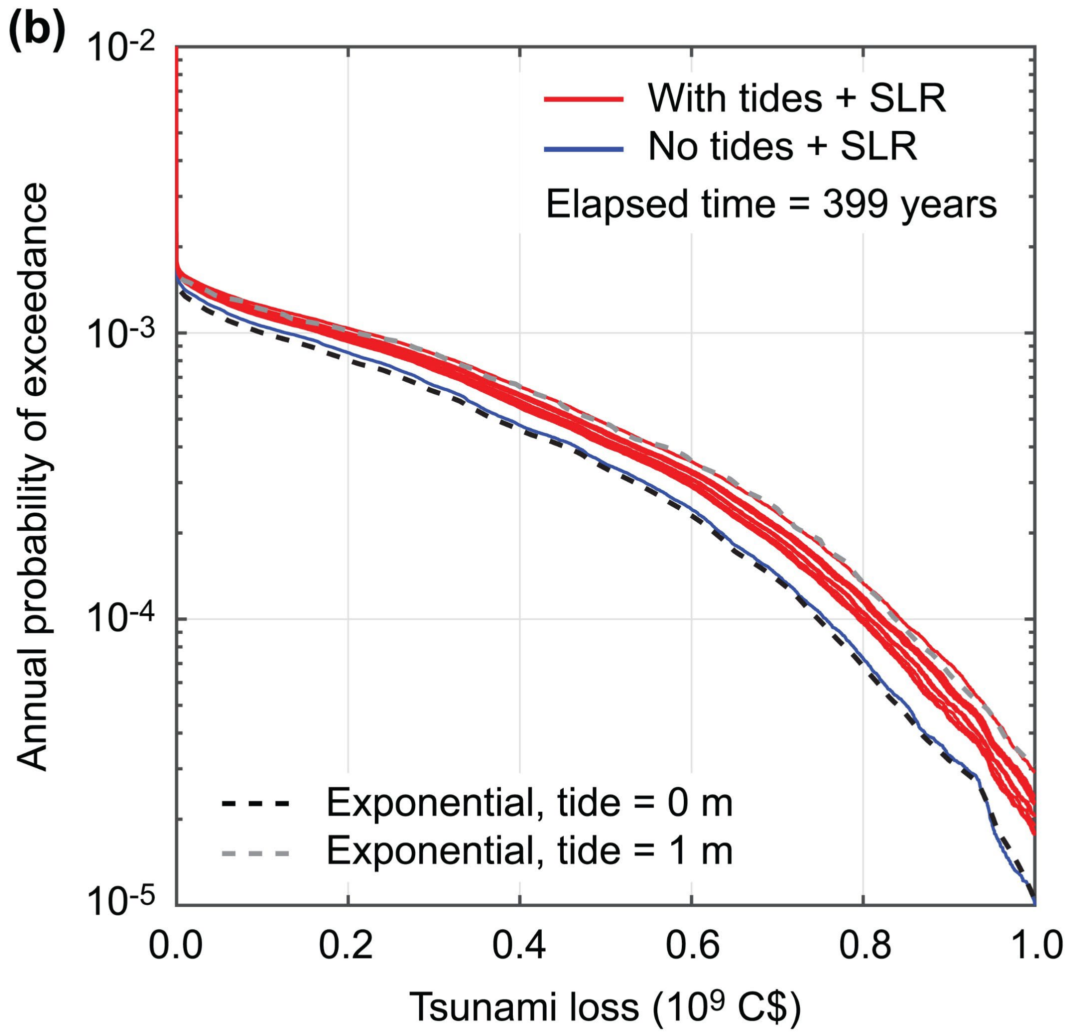
- Time-dependent tsunami risk curves are obtained by considering various elapse times since the last event from 2000 (elapse time of 300 years) to 2100 (elapsed time of 400 years).
- With the progress of elapsed time, tsunami risks increase gradually.
- Note that changes in exposure are not taken into account, which is very important.



# Sea-level Rise Impact on Tsunami Risk Curves

- The effects of different climate scenarios (RCPs) can be important for the future situation.

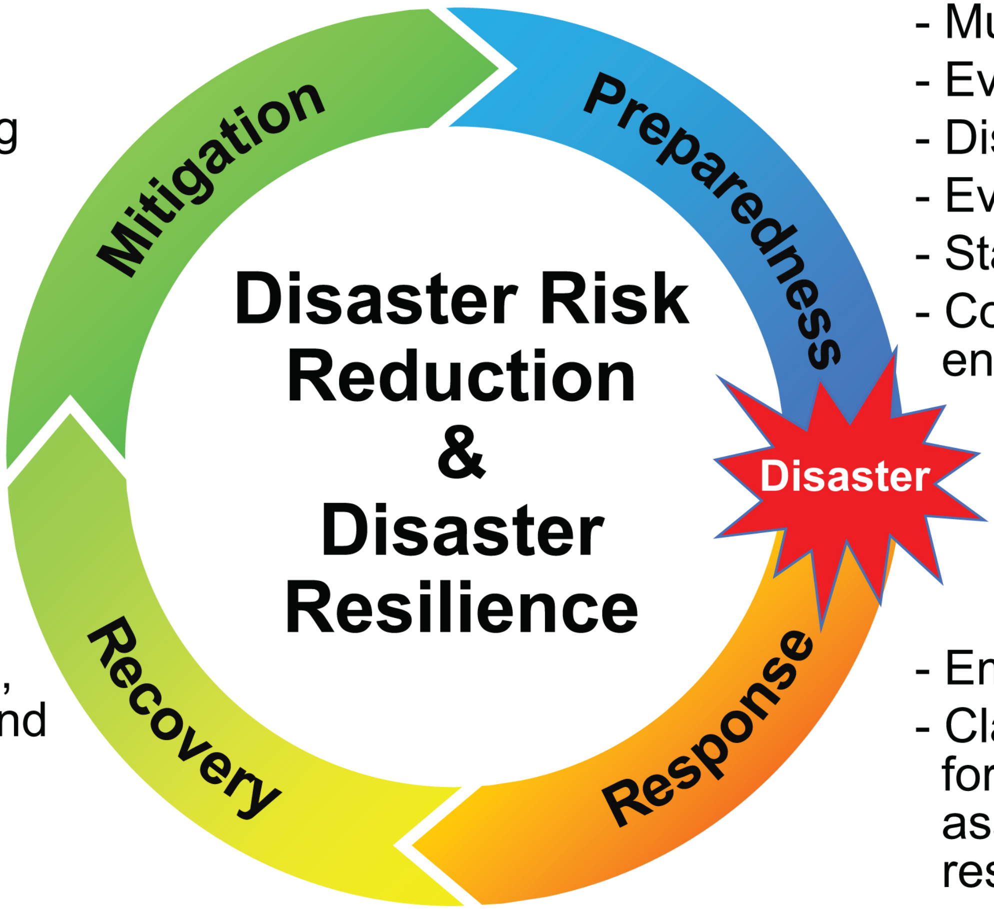


# Current & Future Actions for Disaster Risk Reduction & Resilience for Tofino

- Seismic upgrading of critical facilities (hospital & school)
- Water supply system upgrading
- Increase tsunami signposts
- Vertical evacuation shelter
- Road and power suply risk mitigation

- Multi-hazard risk map
- Evacuation route map
- Disaster education
- Evacuation drills
- Staff training
- Community/business engagement & outreach




- Pre-disaster recovery planning, including business continuity and financial transition plans
- Earthquake insurance take-up

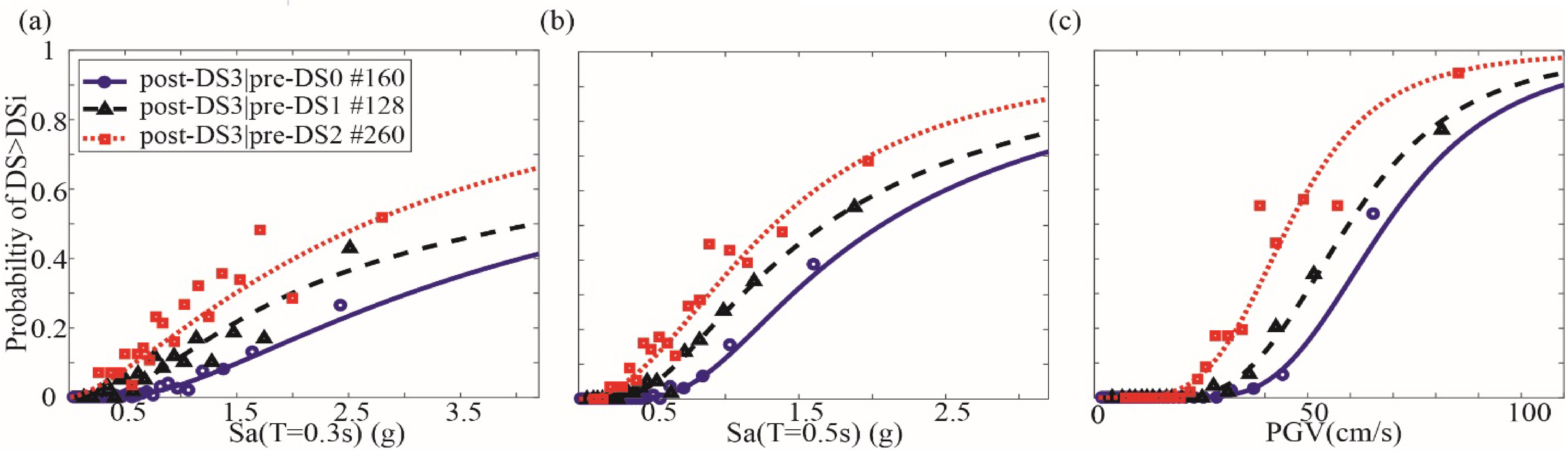
- Emergency response protocols
- Clarification of roles and duties for post-disaster building collapse assessments and search & rescue activities

# Research Need for Improved & Extended Fragility Curves

# Analytical Fragility Curves

Zhang et al. (2020) in EESD

- The concept of analytical fragility curves is well developed in earthquake engineering.
- For example, mainshock-aftershock sequences from the Cascadia subduction earthquake were applied to wooden houses in Victoria, BC, to develop state-dependent seismic fragility curves.



# Need for Artifi

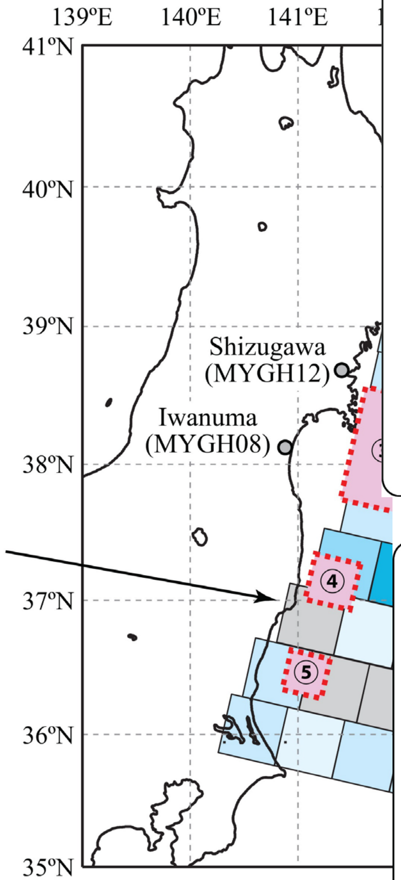
**Frequency-dependent rupture process:**

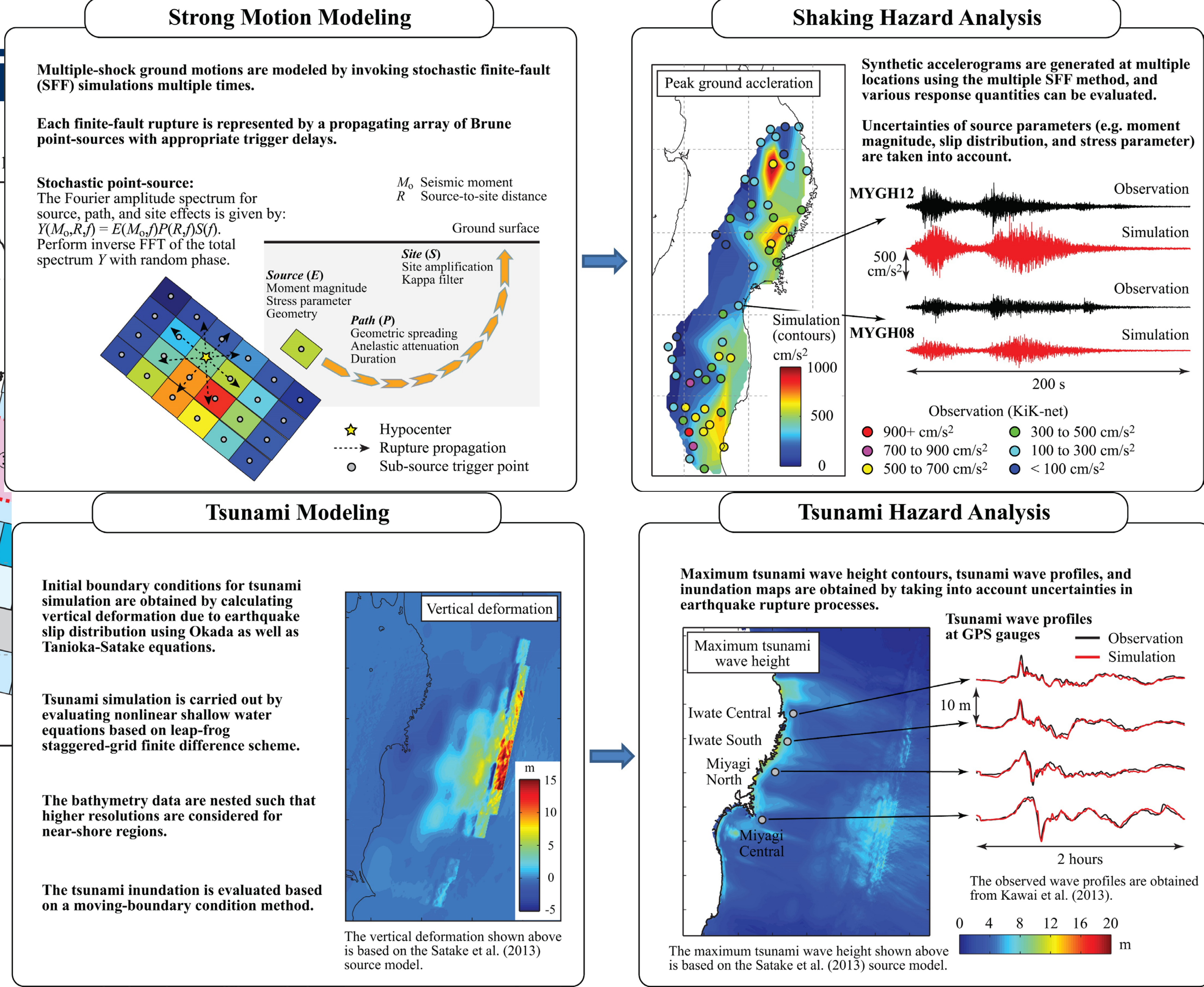
The background fault rupture has influence on low-frequency source process.

The strong motion generation areas have major influence on high-frequency source process.

***Background slip distribution*** can be represented by inverted source models based on low-frequency data (e.g. teleseismic, tsunami, and geodetic).

The slip distribution is based on Satake et al. (2013).

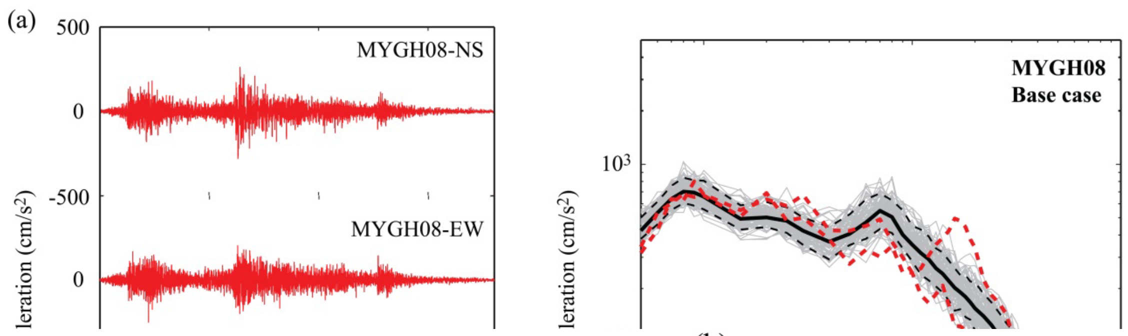


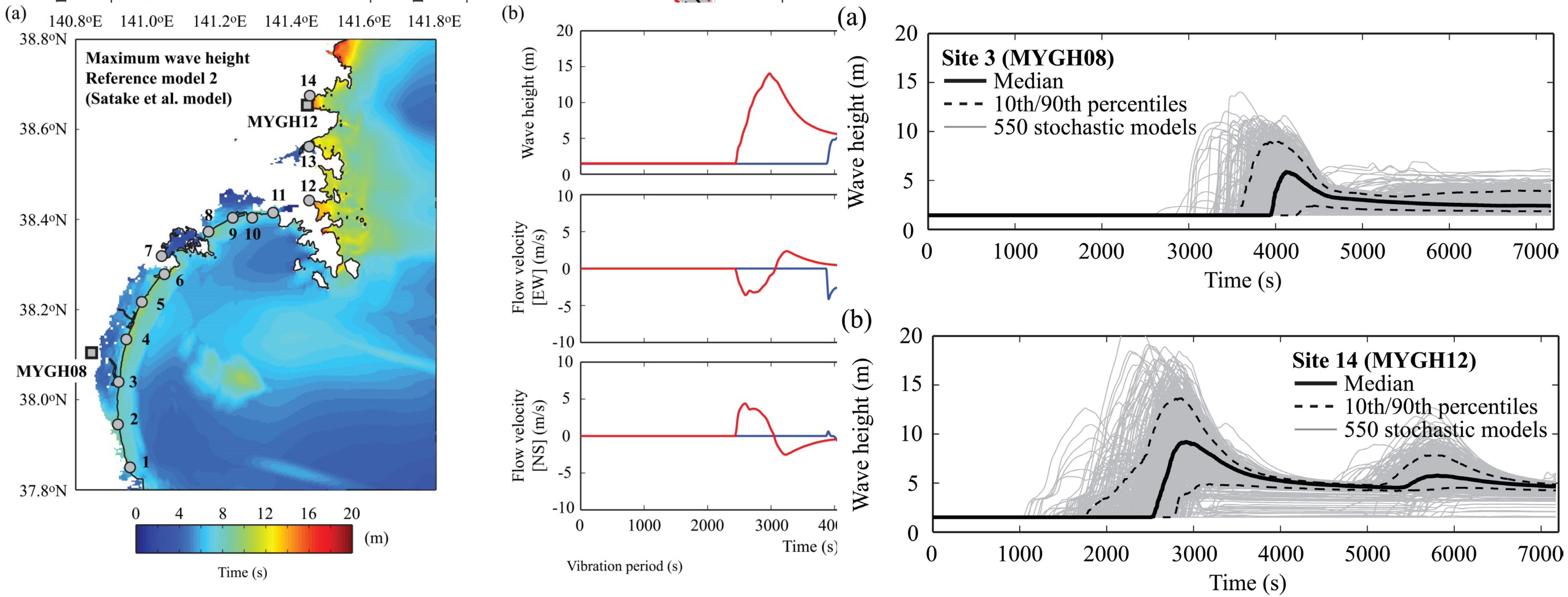

Goda et al. (2017)

inSERRA

# Need for Artificial Shaking-Tsunami Sequences



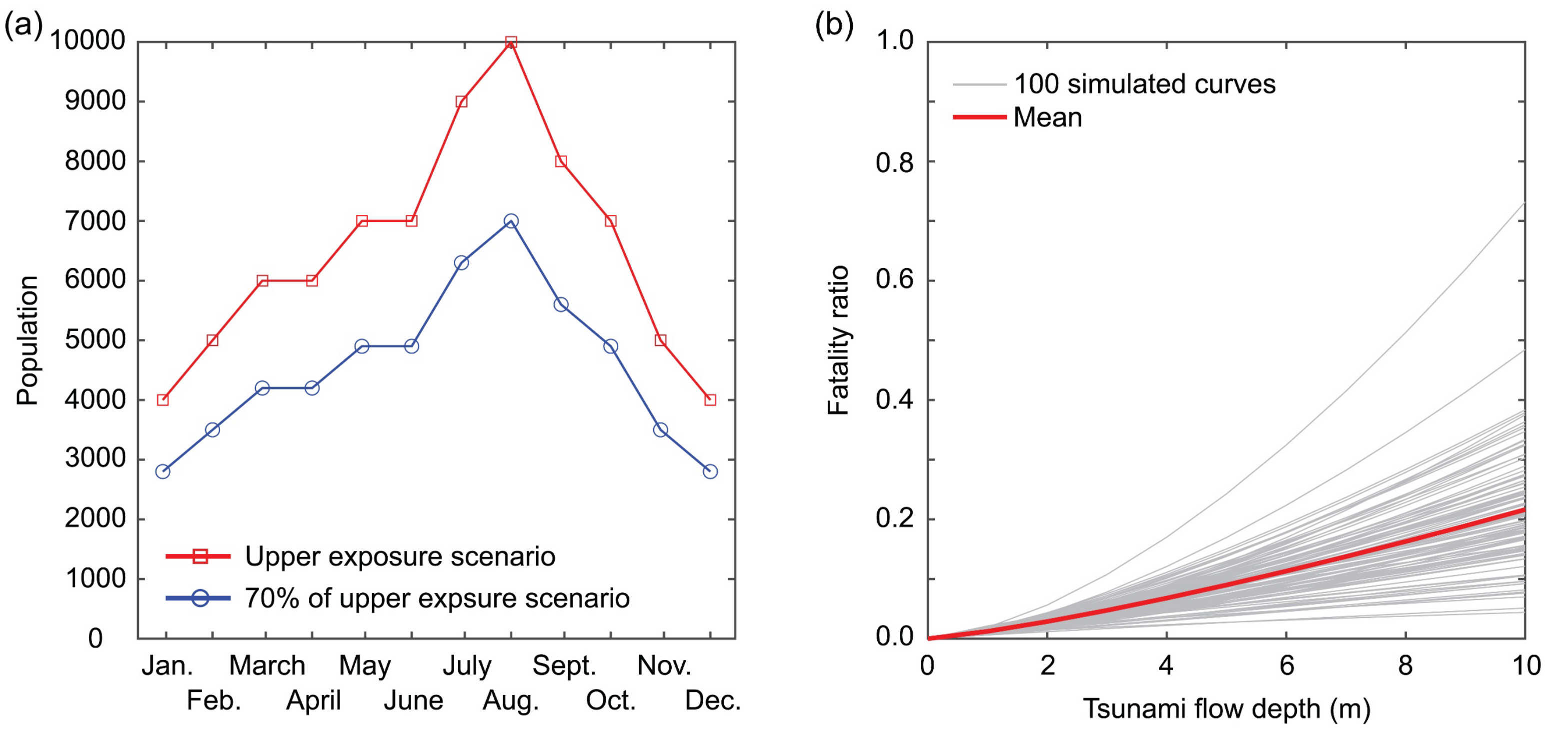

- Comparison of observed and simulated ground motions at MYGH08 (Iwanuma) and MYGH12 (Shizugawa).



# Exposure & Fatality Models

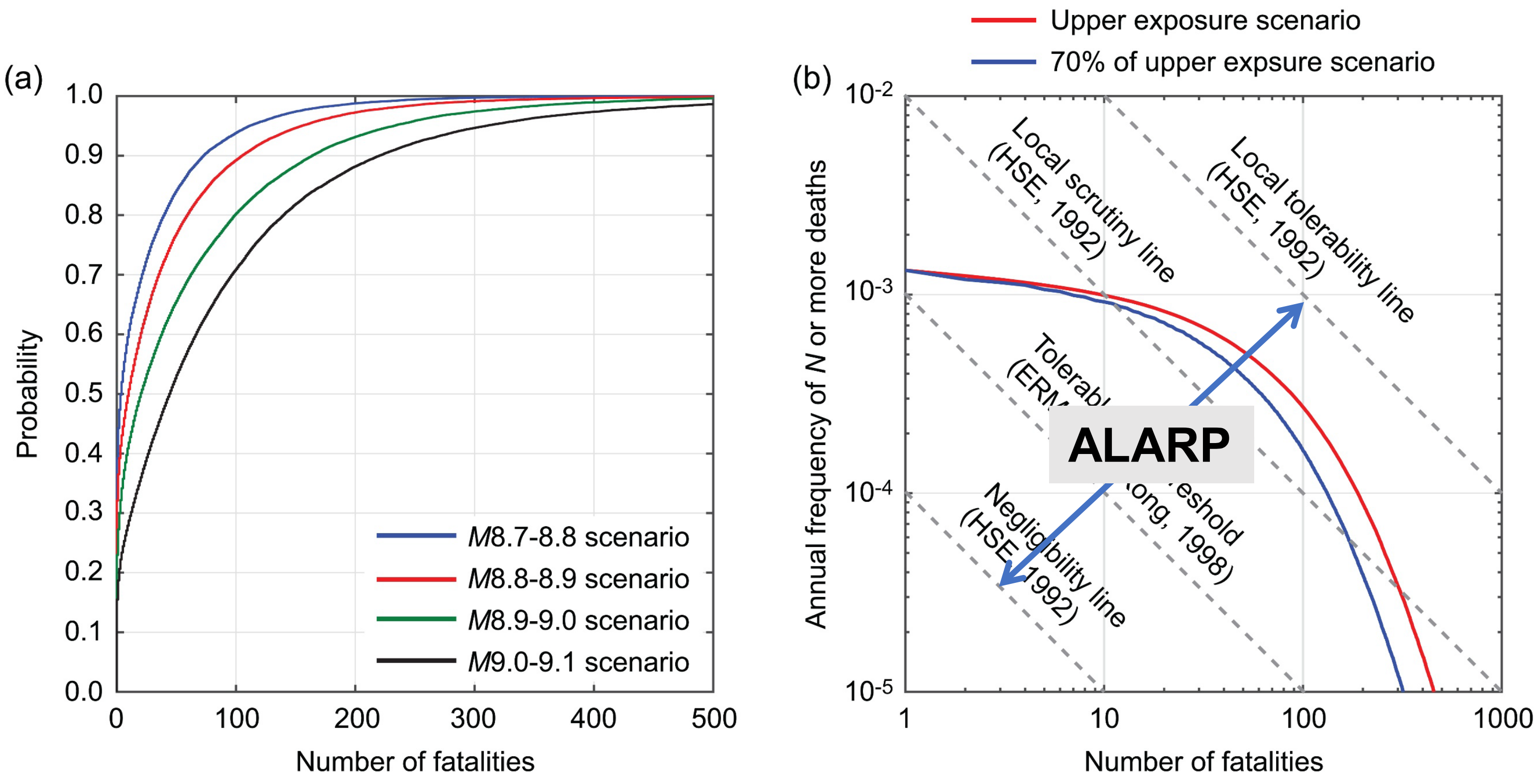
Goda & Evans (2023) in ASCE

- The District of Tofino carried out a detailed exposure (population) survey for tsunami evacuation purposes.
- The summer-time populations are assigned to individual properties.
- The seasonal and daily variations of the population are considered.
- The fatality models by Suppasri et al. (2016) characterize the parametric uncertainty of the fatality ratio as a function of tsunami flow depth.



# Tsunami *F-N* Curves for Tofino

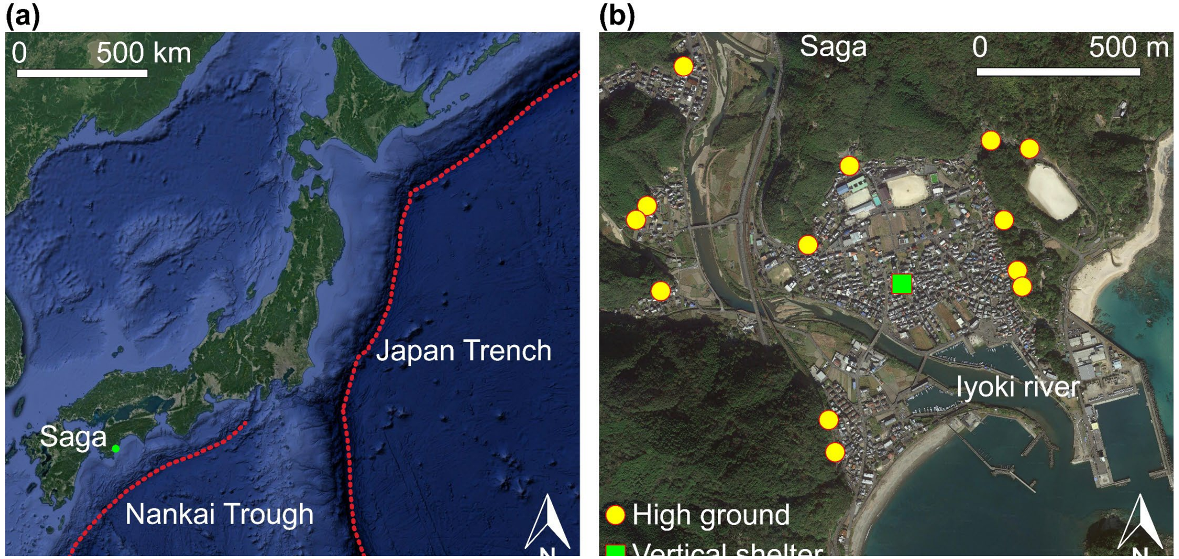
- The stochastic tsunami simulation model, population exposure model, and tsunami fatality model are integrated.
- The conditional probability distributions of the number of fatalities can be evaluated for four magnitude scenarios.
- By accounting for the magnitude-frequency relationship, the unconditional probability distribution of the number of fatalities (i.e., *F-N* curve) is derived.
- The *F-N* curves intersect with the HSE's local scrutiny line -> requires the life safety improvements, if

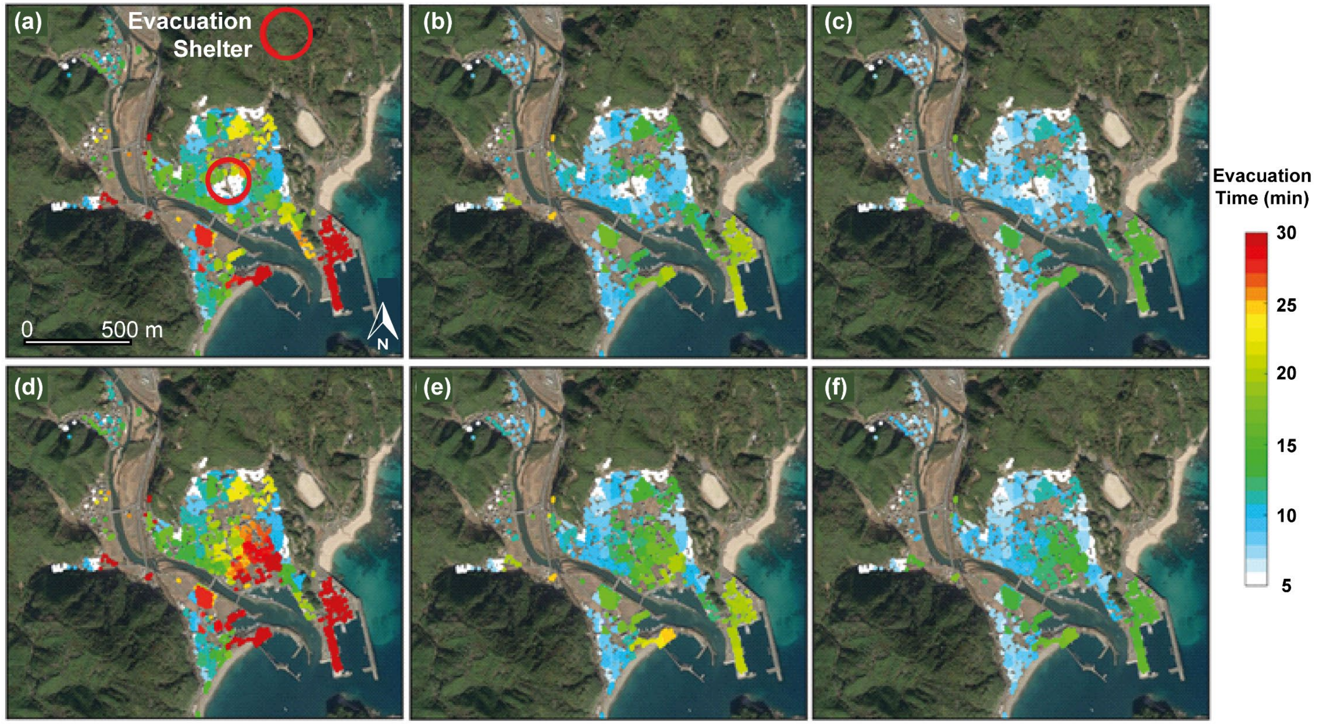


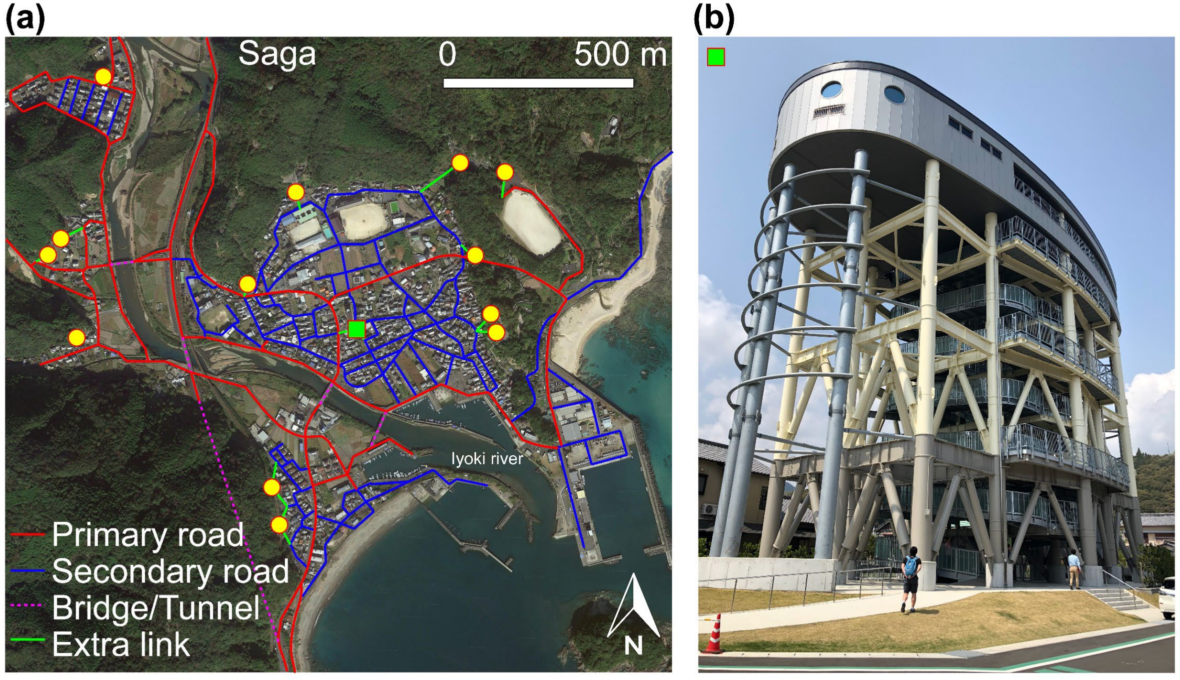
Muhammad et al. (2023) in IJDRR

# Tsunami Warning and Evacuation for Tofino

- Tsunami warning-evacuation can be modeled through agent-based simulations.
- Evacuation simulations could also be used for fatality estimations to develop ‘analytical’ fragility curves for fatalities.



# Future Plan for Tofino

- Coupled strong motion and tsunami simulations for the Cascadia subduction events:
  - Stochastic finite-fault model for the Cascadia events first
  - Physics-based low-frequency ground motion simulations later
- Development of multi-hazard fragility curves (shaking, tsunami, aftershocks, etc.)
- Human fatality model -> Warning and evacuation effects to be simulated through agent-based model
- Multi-hazard risk-based microzonation
- Other hydroclimatic hazards (e.g. coastal flooding)

# Any Questions?

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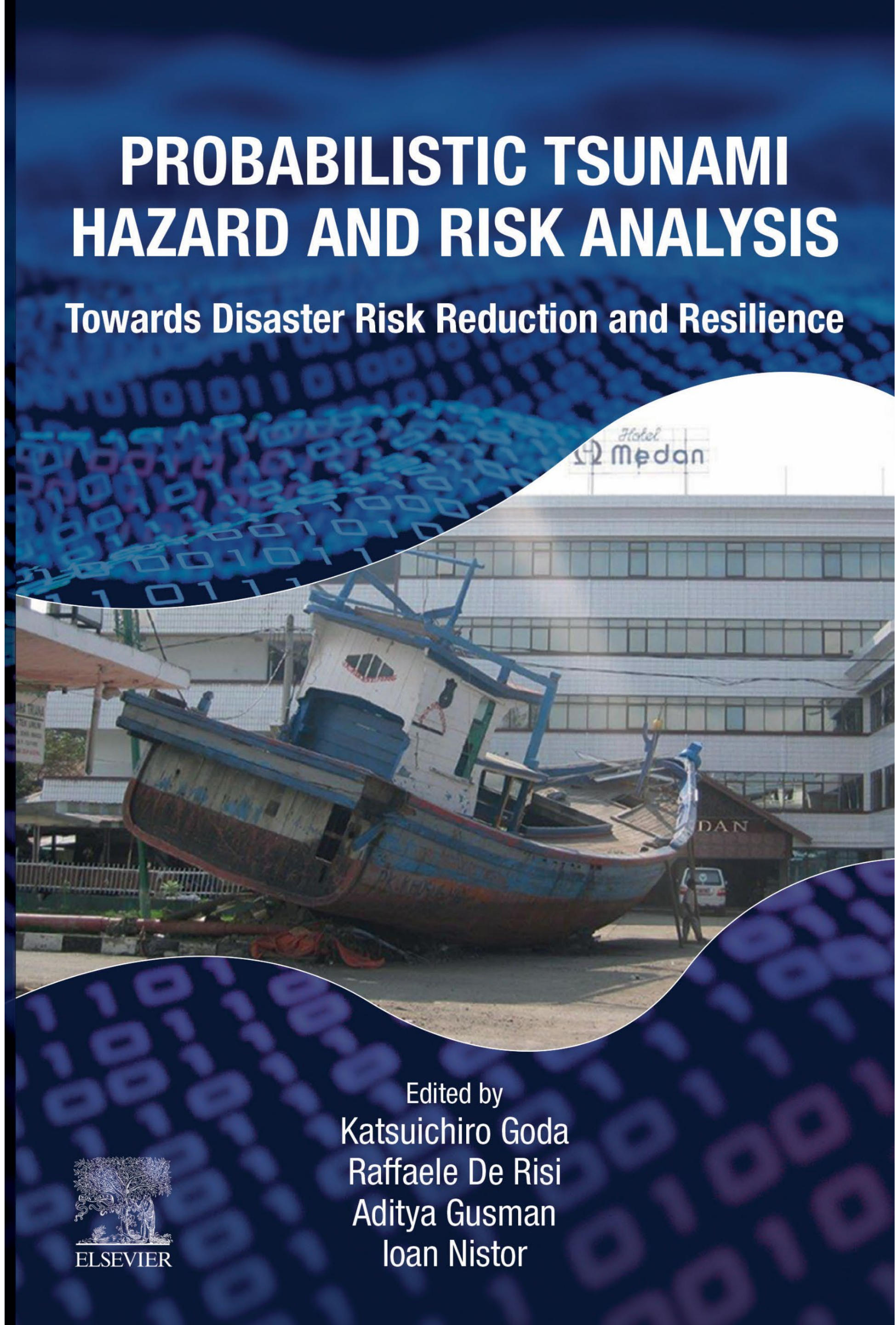
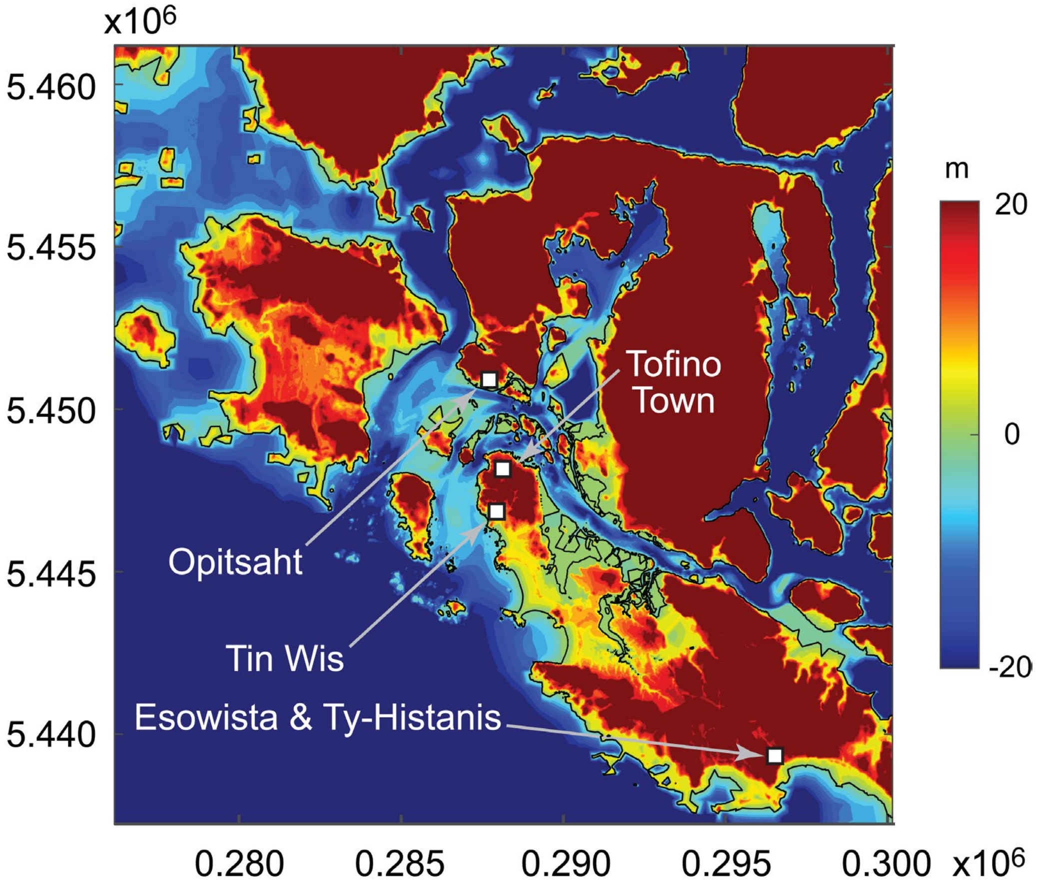
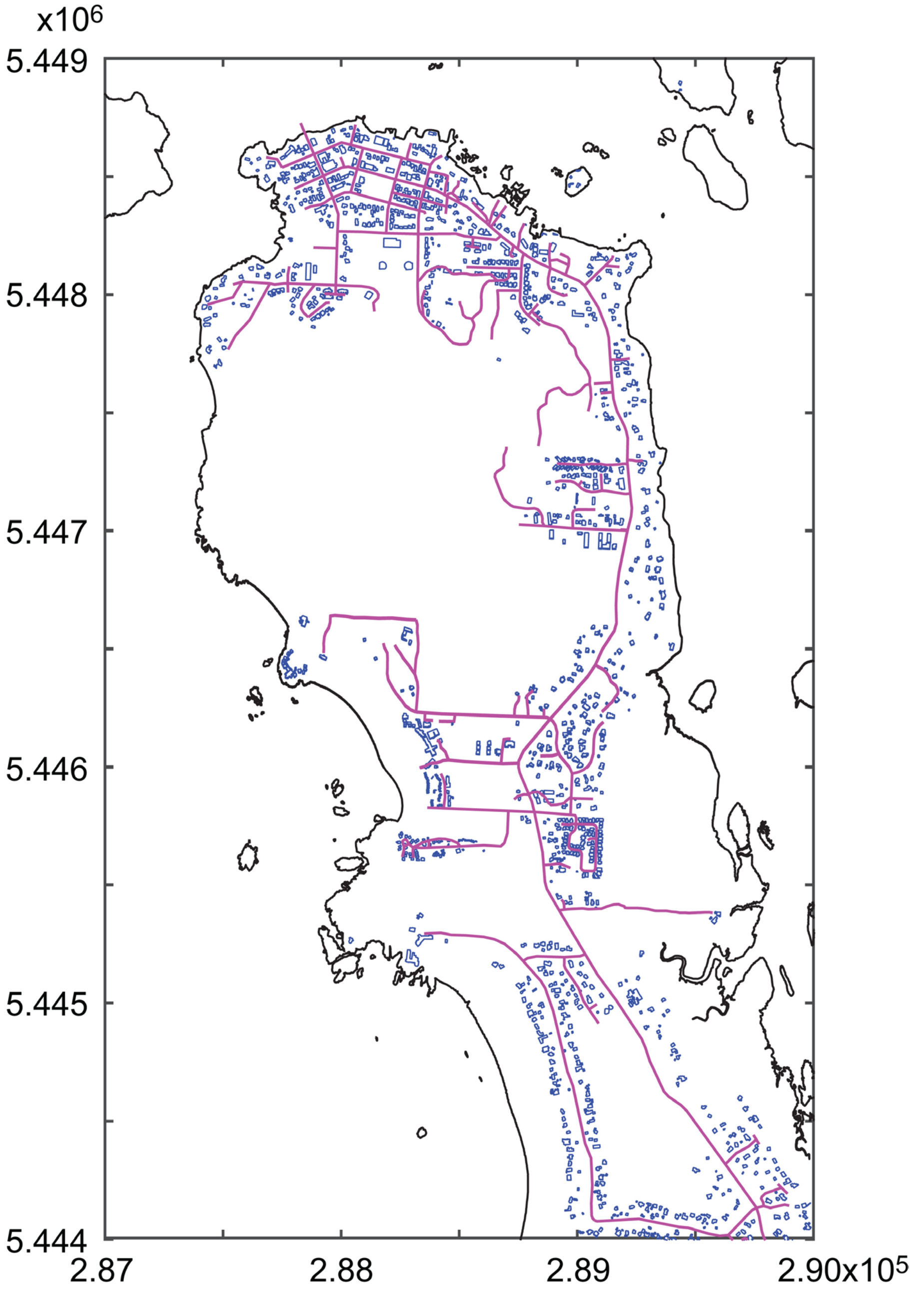


- About 2500 people live in Tofino. There are 2000+ buildings and facilities. In summer, many tourists visit and stay in Tofino.
- Four First Nations communities (Tin-Wis, Esowista, Ty-Histanis, and Opitsaht)

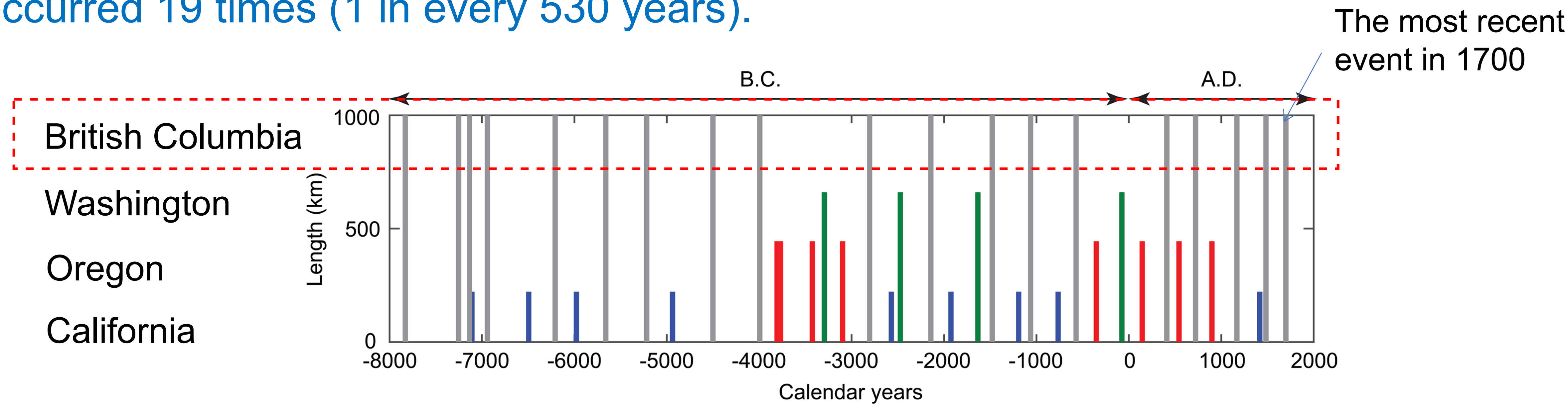


# Influential Hazards

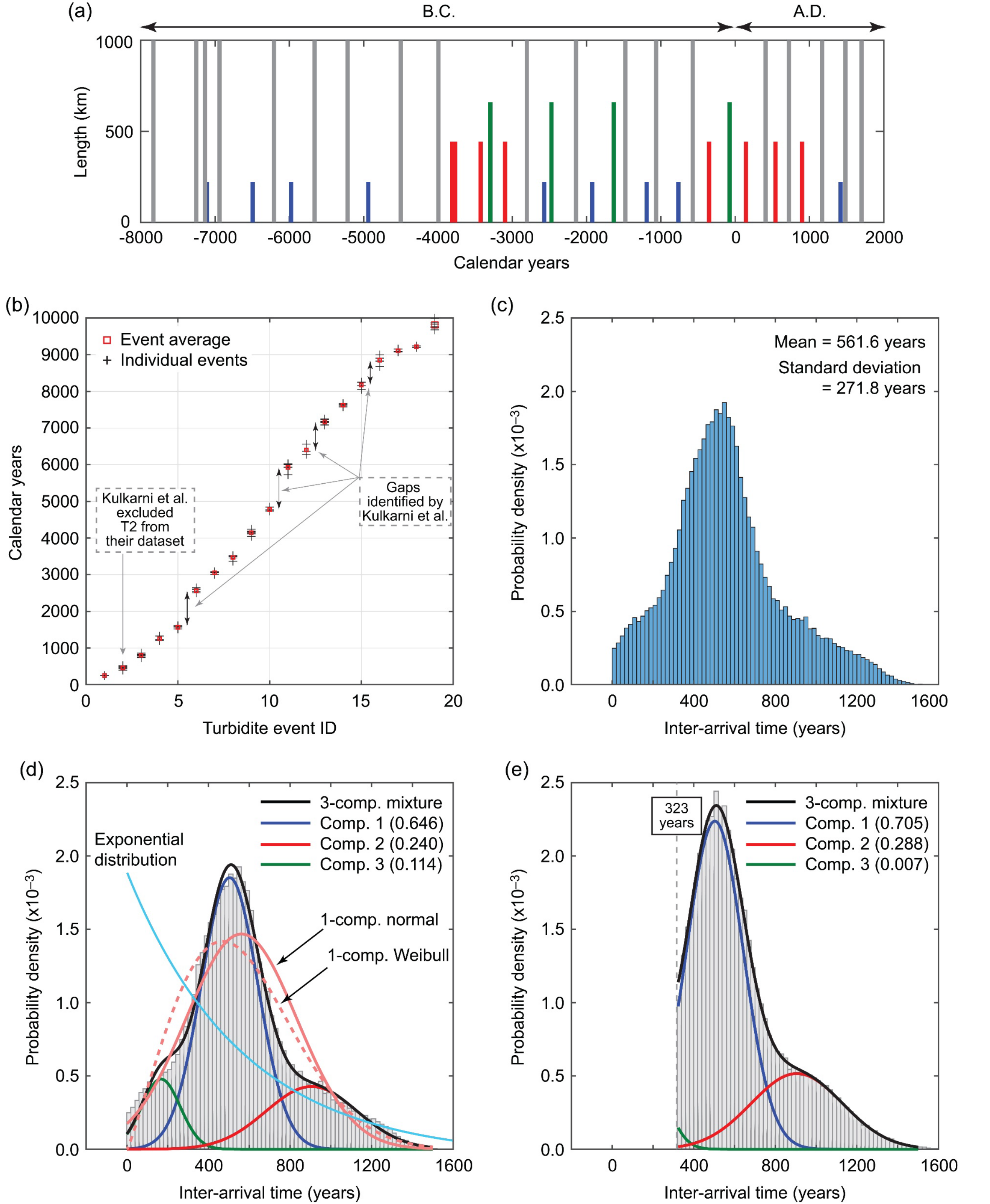
# Historical Events in Cascadia

- In the past, various geological and geophysical investigations have been conducted to determine the frequency of major subduction earthquakes (*M*8.0 and above).
- The offshore turbidite history by Goldfinger et al. (2012) indicates that 40 events occurred over the last 10,000 years (1 in every 250 years).
- Among these historical events, a full rupture (extending to Vancouver Island) occurred 19 times (1 in every 530 years).



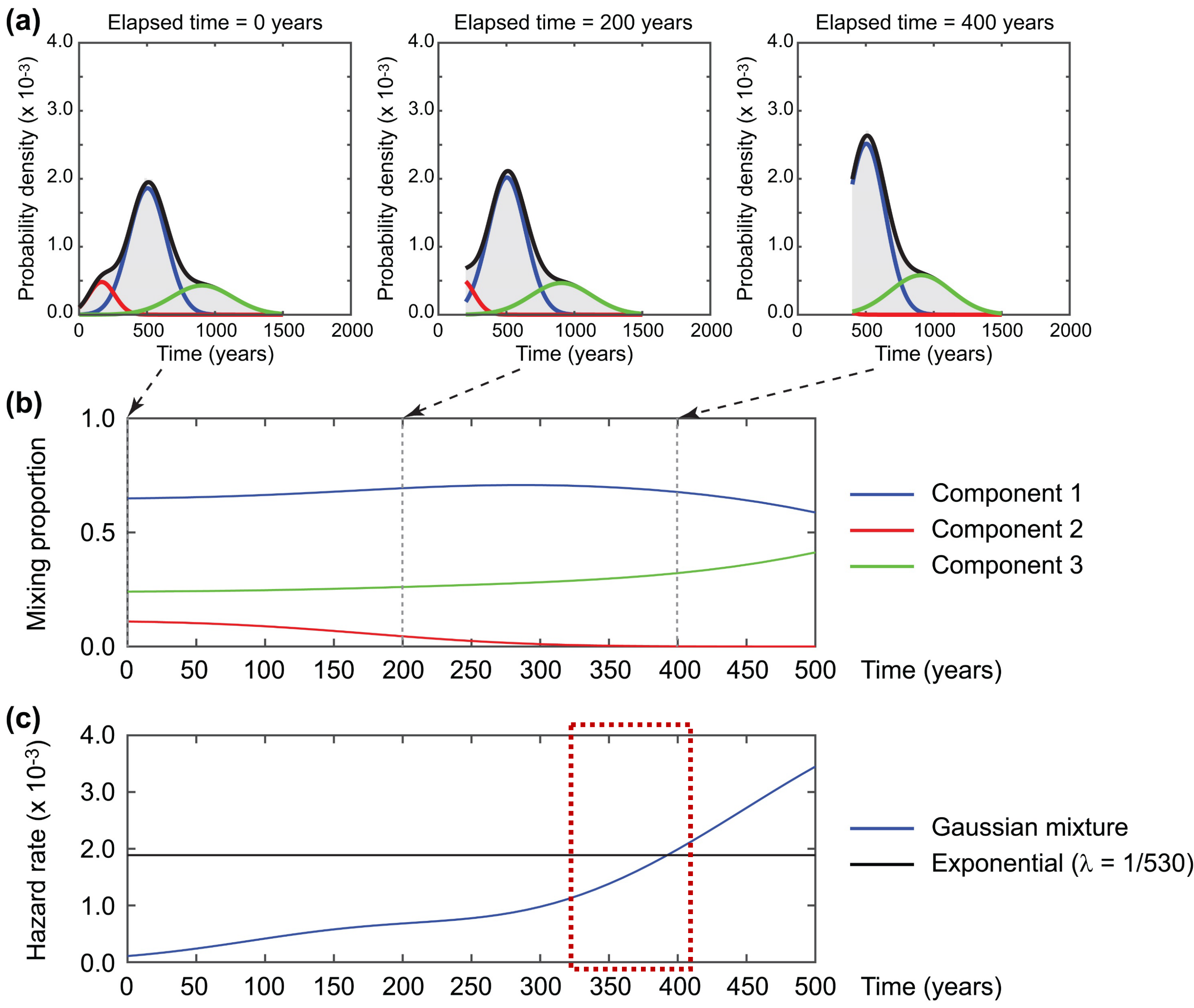
# Time-dependent Earthquake Occurrence Model

- The earthquake occurrence history of the Cascadia full-ruptures shows clustering and gaps.
- The radiocarbon dating of the turbidite data involves uncertainty (c. 100 years).
- The resampling of the earthquake occurrence dates is carried out by considering the data uncertainty.
- A Gaussian mixture model with 3 components is fitted to the resampled earthquake inter-arrival data.



# Gaussian Mixture Renewal Model for the Full-rupture Cascadia Events

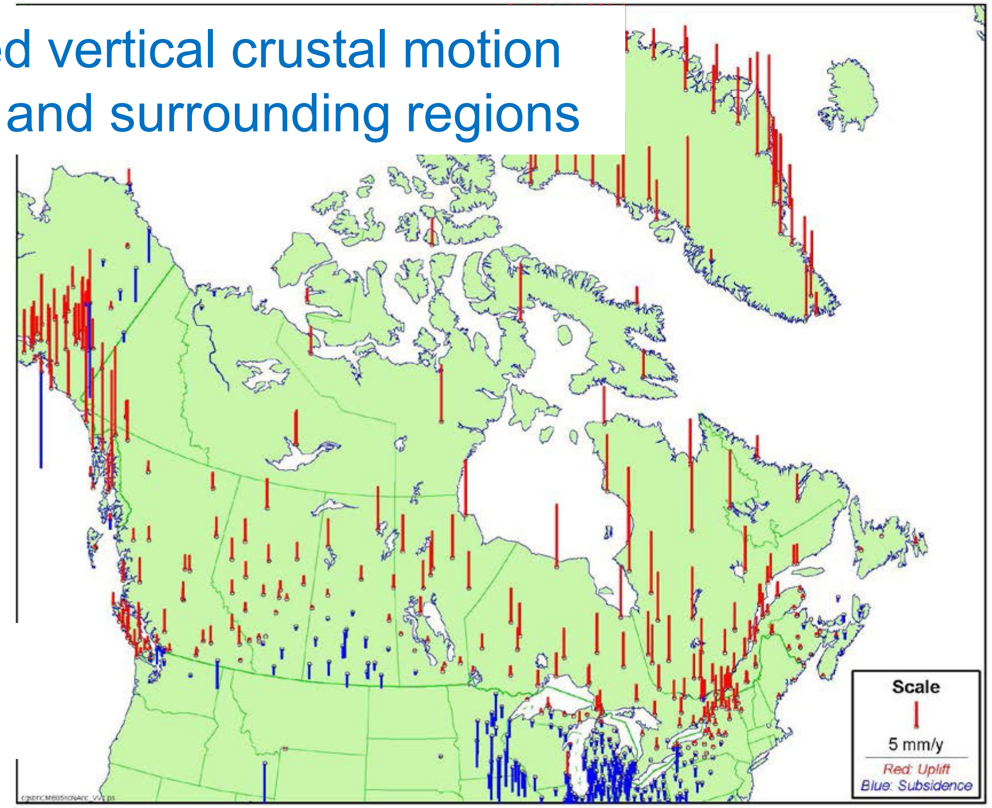
- The time-dependent estimates of the full-rupture event shows that the hazard rate (i.e., conditional probability given a current elapsed time since the last event in 1700) is less than the time-independent hazard rate at the present.
- This order will be reversed by Year 2100.



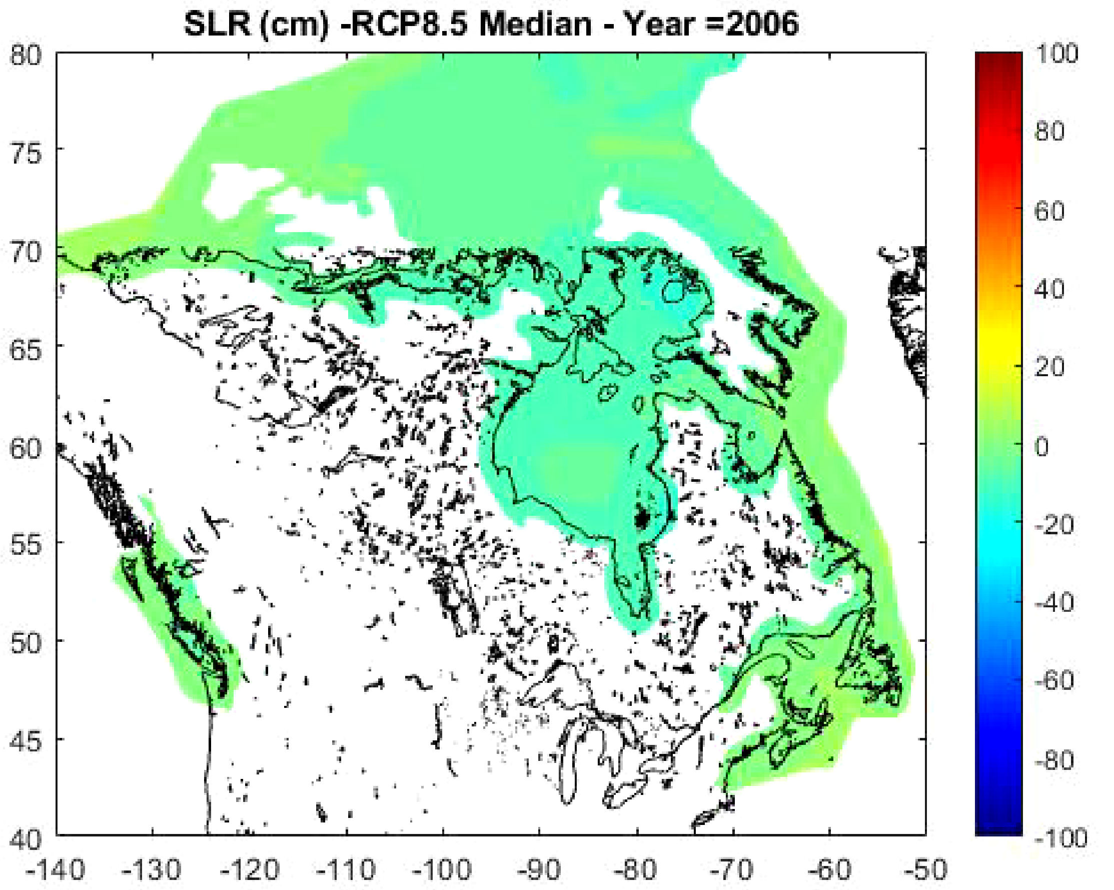
# Future Relative Sea Level Rise

- The crust is in motion. Many locations in Canada experience uplift because of glacial isostatic adjustment, or postglacial rebound. This effect must be considered when the sea level rise is evaluated (i.e., the sea level rise solely due to climate change is reduced).

GPS-derived vertical crustal motion for Canada and surrounding regions

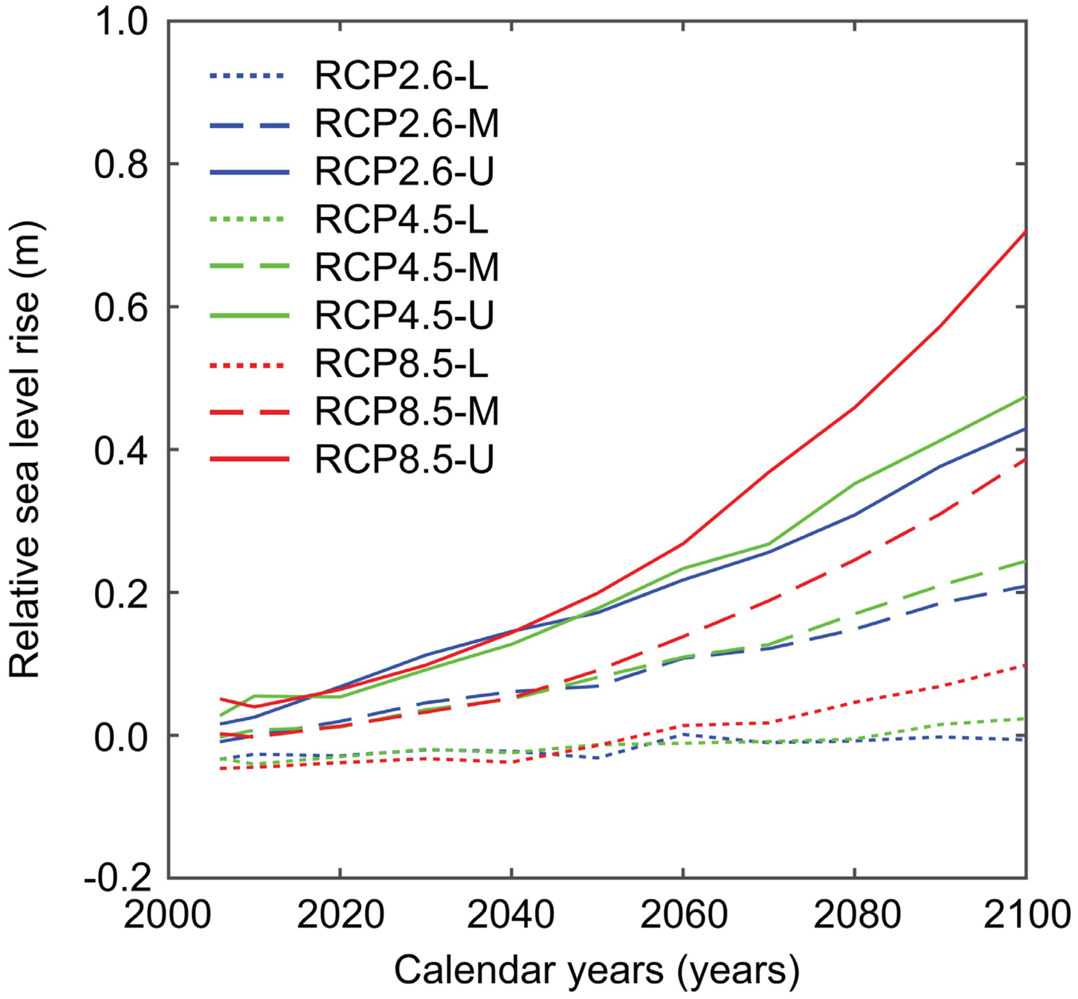



James et al. (2021)



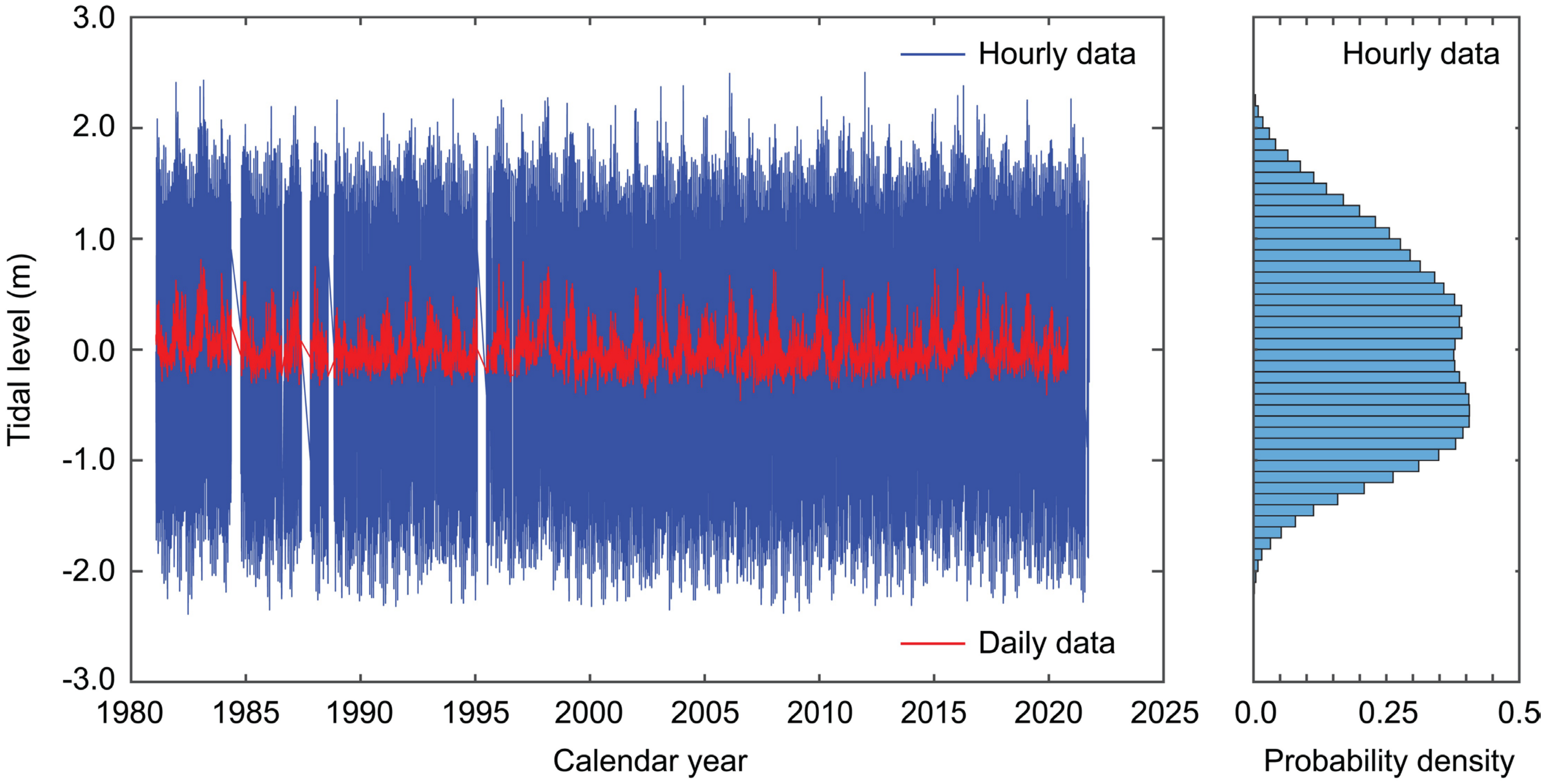
# Relative Sea Level Rise in Tofino

- James et al. (2021) produced the national relative sea level projections for Canada based on the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC-AR5) by accounting for the vertical land motion for Canada based on GPS observations.
- In Tofino, +0.7 m relative sea level rise can be expected under the RCP8.5-Upper scenario.



# Tidal Levels in Tofino

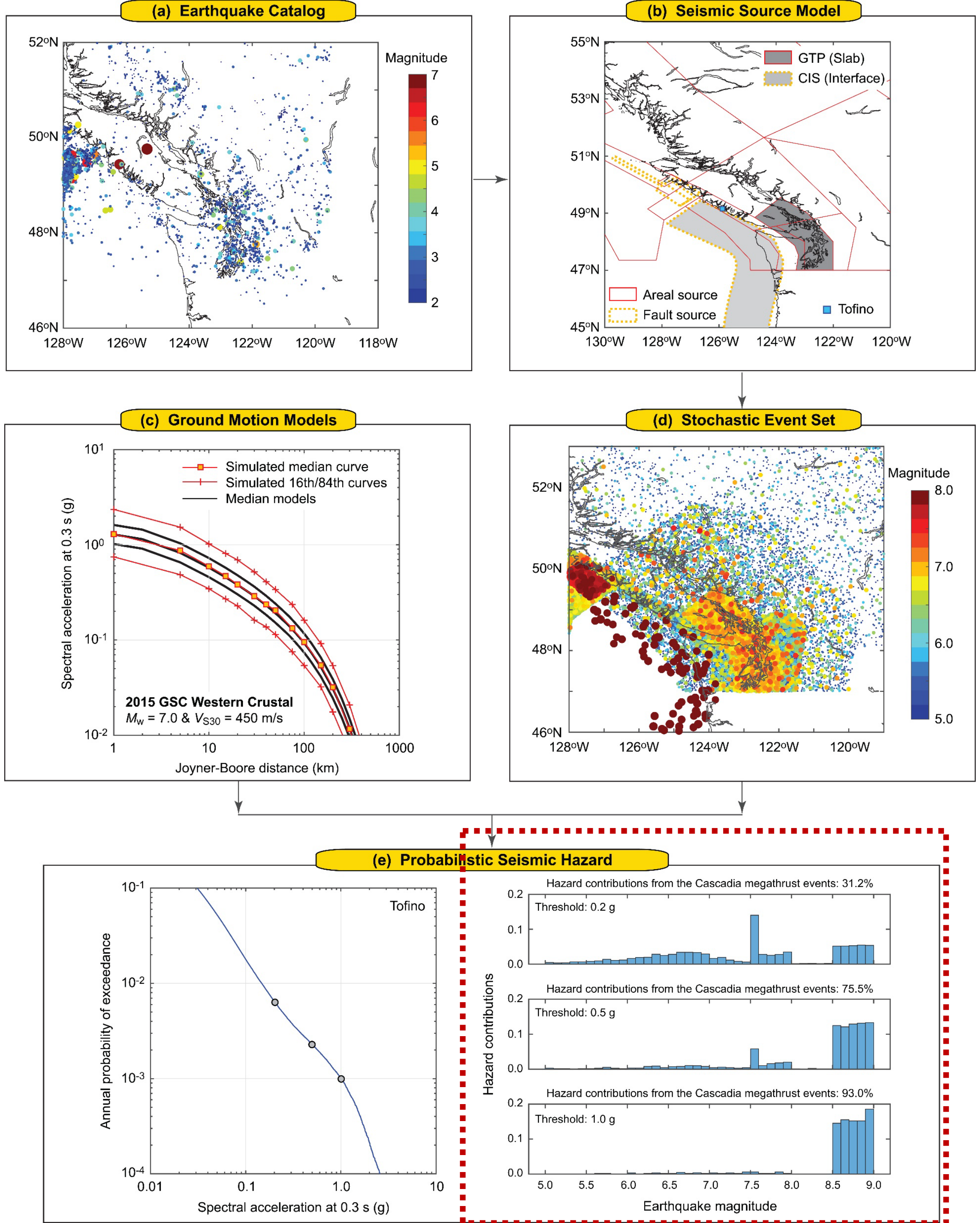
- A tidal monitoring station has been operational in Tofino since 1909.
- The hourly tidal data vary between –2 m and +2 m with respect to the long-term average tidal level.
- Assuming the tidal fluctuation remains similar in the future, the fluctuating tide can be sampled from the hourly tide data in Tofino.



# Multi-hazard Risk Framework

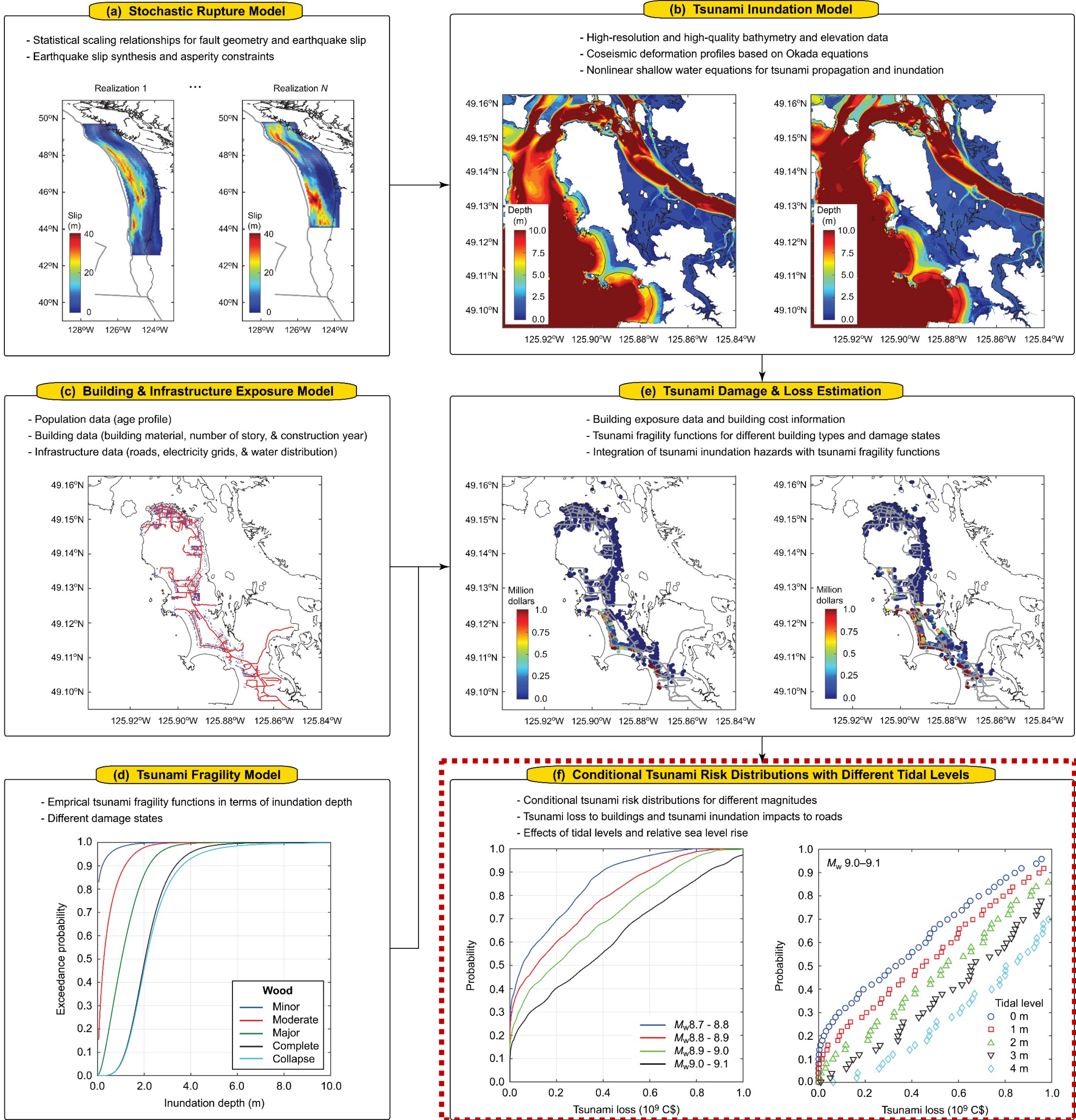
# Earthquake Risk Assessment for Non-tsunamigenic Events

- Earthquake hazards due to non-tsunamigenic events are evaluated using the Geological Survey of Canada model.
- For Tofino, hazard contributions from megathrust Cascadia subduction events are dominant compared with crustal and inslab events.



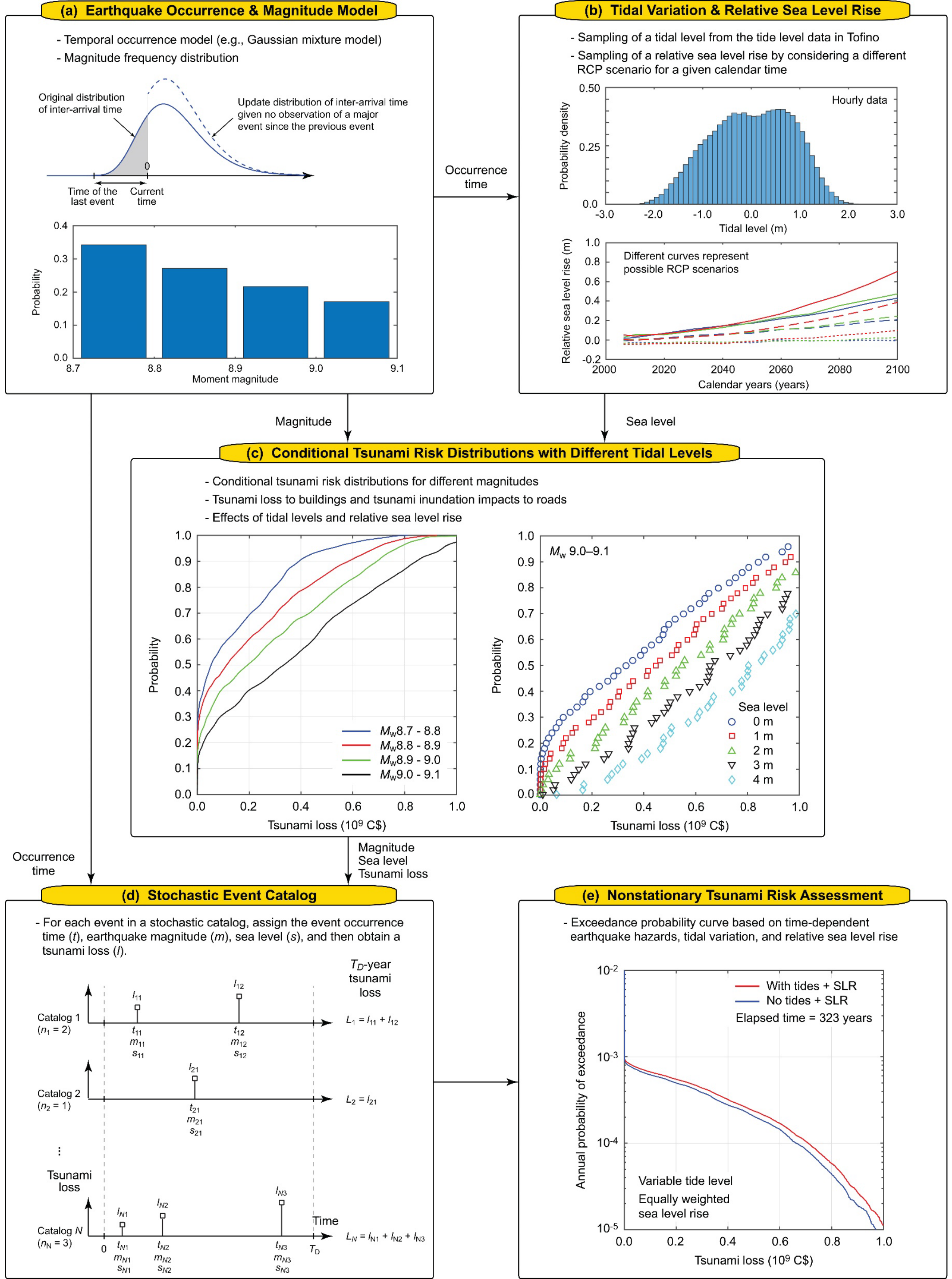
# Conditional Tsunami Risk Distributions by Considering Different Tidal Levels

- Tsunami risk calculations are demanding computationally because of numerous runs of high-resolution inundation simulations (5-m grids) for many stochastic sources (+2000).
- The effects of relative sea level rise or tidal level can increase computations significantly.



# Probabilistic Tsunami Risk Analysis for Time-dependent Hazards and Nonstationary Sea Levels

- The long-term multi-hazard risk assessment requires the integration of time-dependent earthquake hazards, non-tsunamigenic sources, tidal variation, and sea level rise effects.
- The final output can be expressed as an exceedance probability curve for a risk estimate of interest (e.g., multi-hazard loss for a building portfolio).

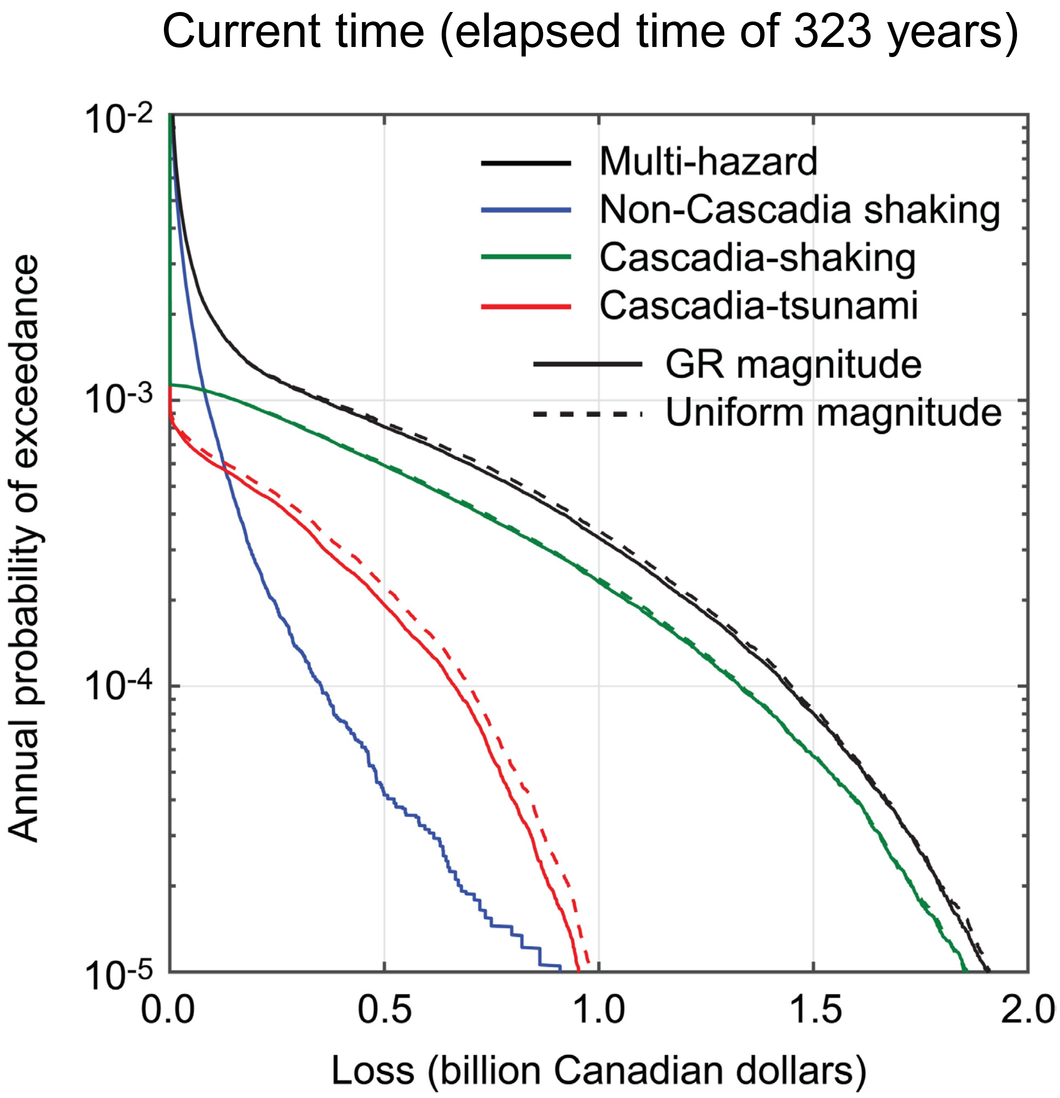


# Result Part 1: Multi-hazard Risk Assessments

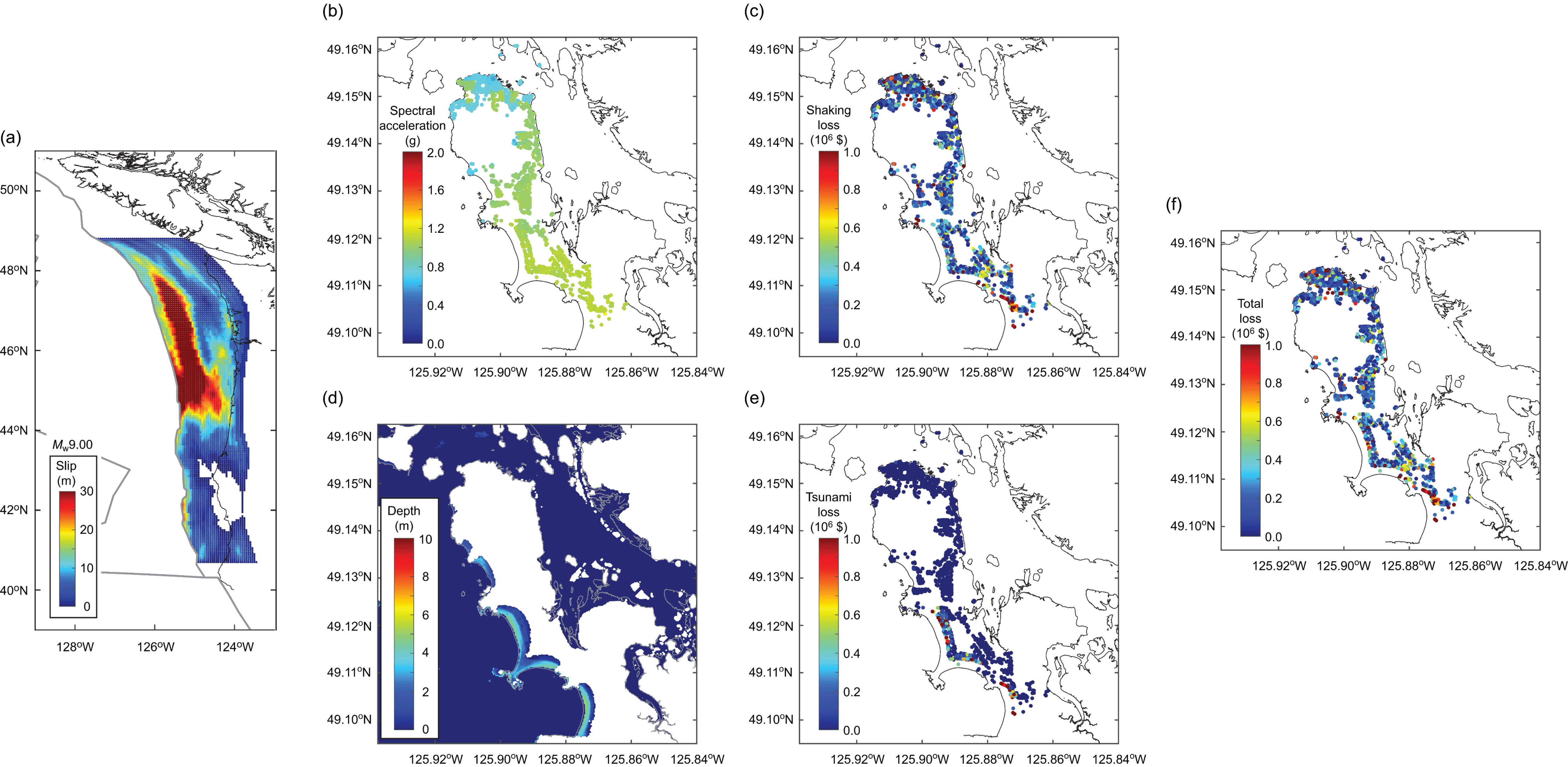
## - Shaking vs Inundation & Non-tsunamigenic vs Tsunamigenic Sources -

# Multi-hazard Exceedance Probability (Risk) Curves

- Multi-hazard risk curves are obtained by considering the average tide conditions.
- The risk curves are decomposed into non-tsunamigenic earthquake risks, tsunamigenic earthquake risks, and tsunami risks.
- The Cascadia earthquake risks are most significant due to the proximity to the subduction zone.
- The Cascadia tsunami risks are approximately half of the Cascadia earthquake risks.



# Multi-hazard Maps for Return Period of 1000 years

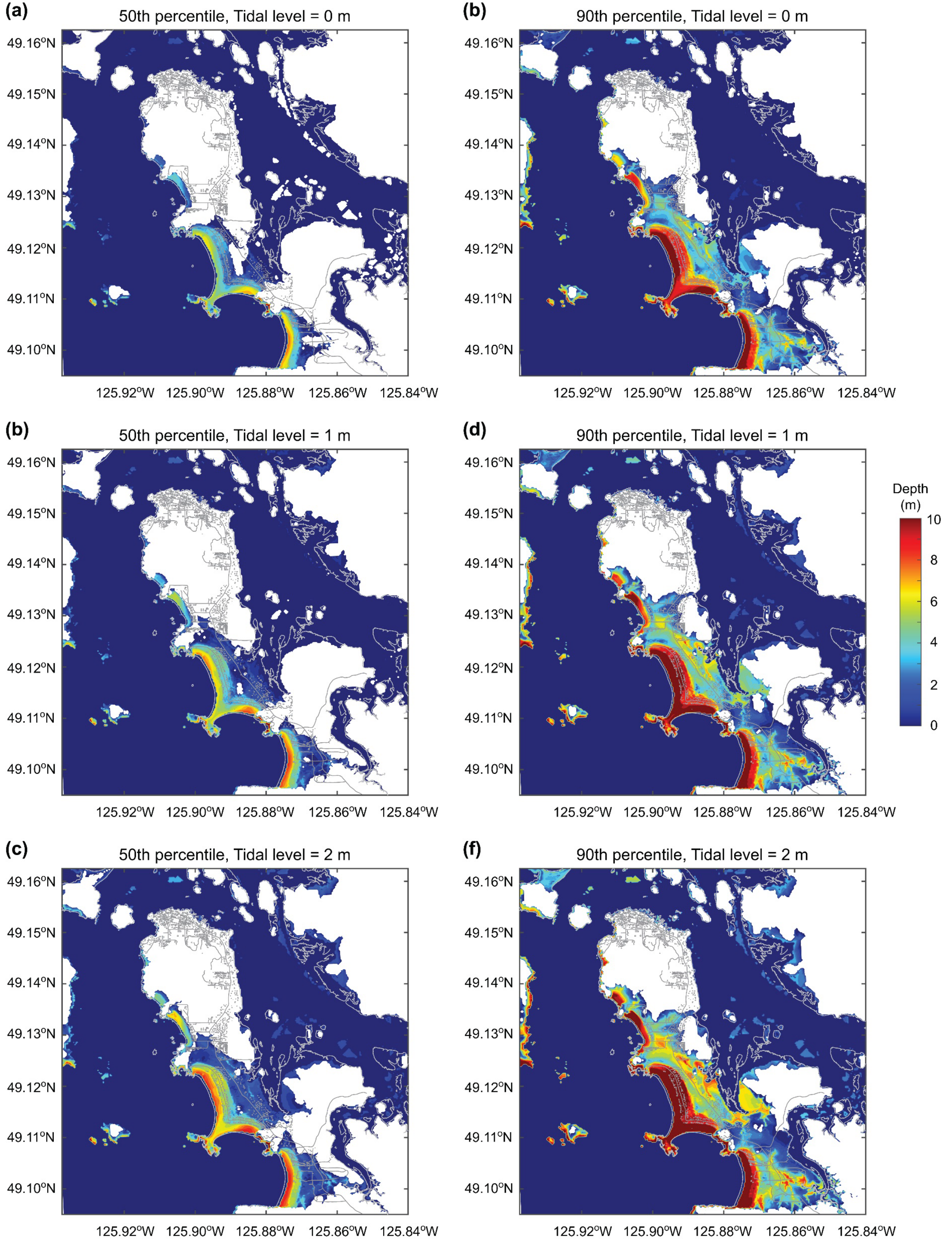


# Result Part 2: Long-term Tsunami Risk Assessments

- Time-dependent Hazards & Tidal and Relative Sea Level Rise Effects -

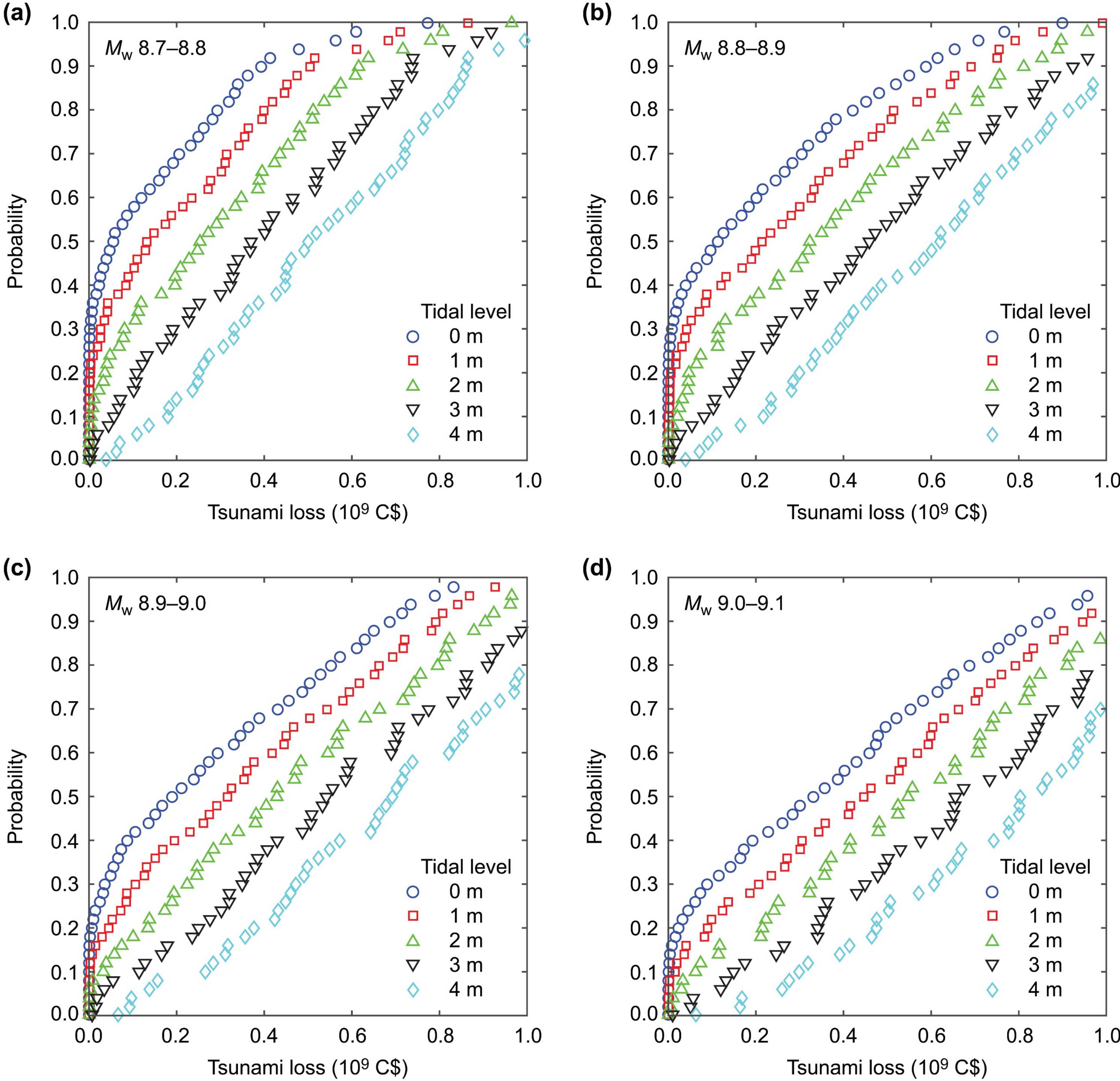
# Effects of Tidal Levels on Tsunami Inundation

- Tidal levels can have major impacts on tsunami inundations.
- For two *M*9 scenarios, tsunami inundation results for three tidal levels (0 m, 1 m, and 2 m) are shown.
- The effects of tidal levels on inundation extent are nonlinear (even though the effects on the wave amplitude are linear and monotonic).



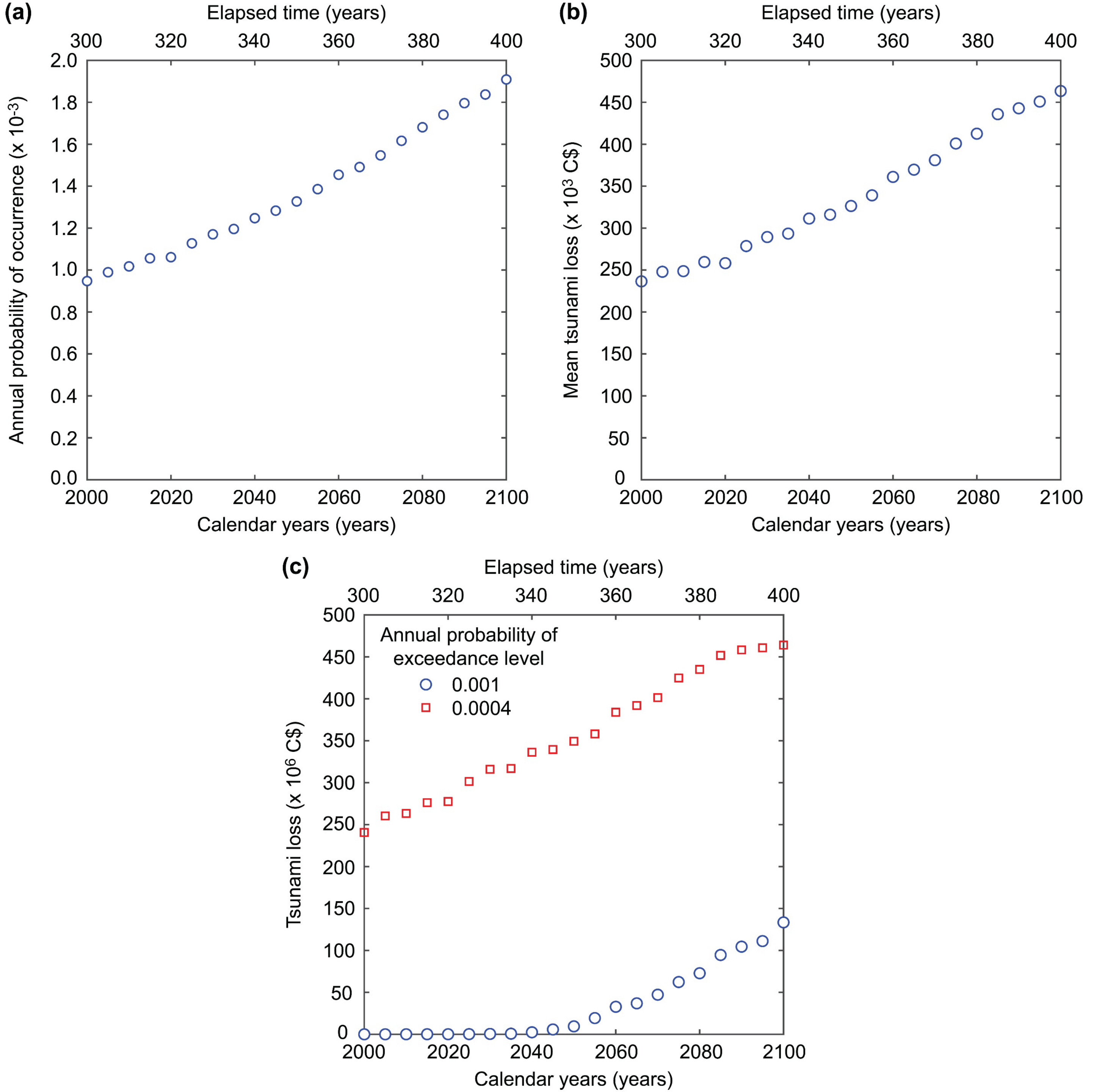
# Effects of Tidal Levels on Tsunami Inundation

- The conditional tsunami risk distributions for different tidal levels are evaluated.
- The considered rupture scenarios are originally based on 2000 stochastic source models.
- To reduce the computations, the scenarios are ordered based on the tsunami risk and only 204 scenarios are run for each tidal level.



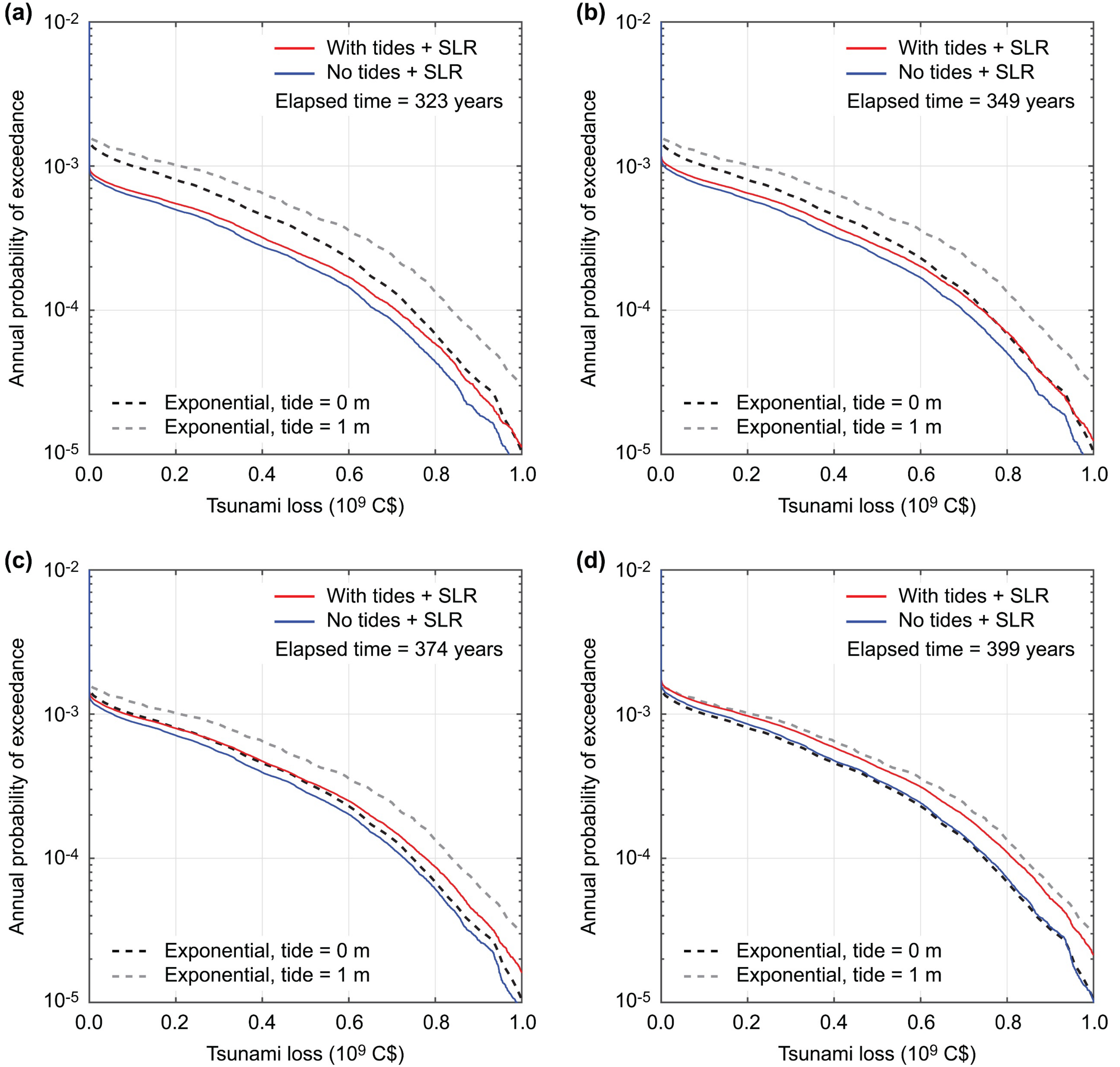
# Effects of Elapsed Time on Tsunami Risk Metrics

- Similarly to the tsunami risk curves, tsunami risk metrics, such as annual probability of loss occurrence, mean tsunami loss, and tsunami loss at 0.001 and 0.0004 exceedance probability level (value at risk), increases gradually.



# Effects of Elapsed Time & Tidal Level on Tsunami Risk Curves

- The combined tidal effect (tidal variation and relative sea level rise) can have noticeable impacts (blue vs red).
- The conventional time-dependent hazard together with a higher-than-average tidal level serves well as conservative estimate presently. This is not guaranteed for a future situation.



# Cascading and Compounding Multi-hazards for Coastal Communities

- The developed multi-hazard tsunami risk model can be useful for various risk management decisions. It can generate extreme multi-hazard scenarios.
- Hydroclimate risks (coastal flooding) and other hazards (landslides and aftershocks) can be added. The interaction among the multiple hazards must be characterized.