Training/Workshop on

Tsunami Evacuation Maps, Plans, and Procedures and the UNESCO-IOC Tsunami Ready Recognition Programme for the Indian Ocean Member States

Hyderabad - India, 15-23 April 2025

Tsunami Inundation Modelling and MAP

TIMM #: Probabilistic vs Deterministic Tsunami Hazard Assessment

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The Indian Ocean Tsunami Hazard Assessment

1) To improve preparedness by enabling national and international disaster managers to address broad mitigation issues:

   - How often will large tsunamis in the Indian Ocean occur?
   - Was the 2004 IOT the "worst case", or does the potential for even higher impacts exist?
   - Which source zones are most important, and for whom?

2) To provide a base level of information for more detailed, smaller scale hazard and risk assessments.

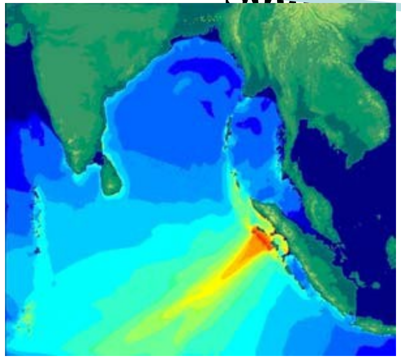
3) To document the state of knowledge, and the lack thereof, of Indian Ocean tsunamis.

Key Steps in Hazard Assessment

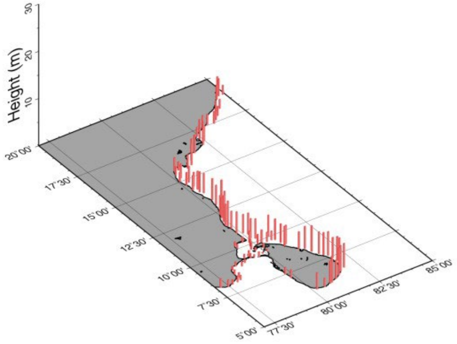
Tsunami Hazard Source → Exposure → Tsunami Hazard Impact on Land

↓

MODELLING TOOLS



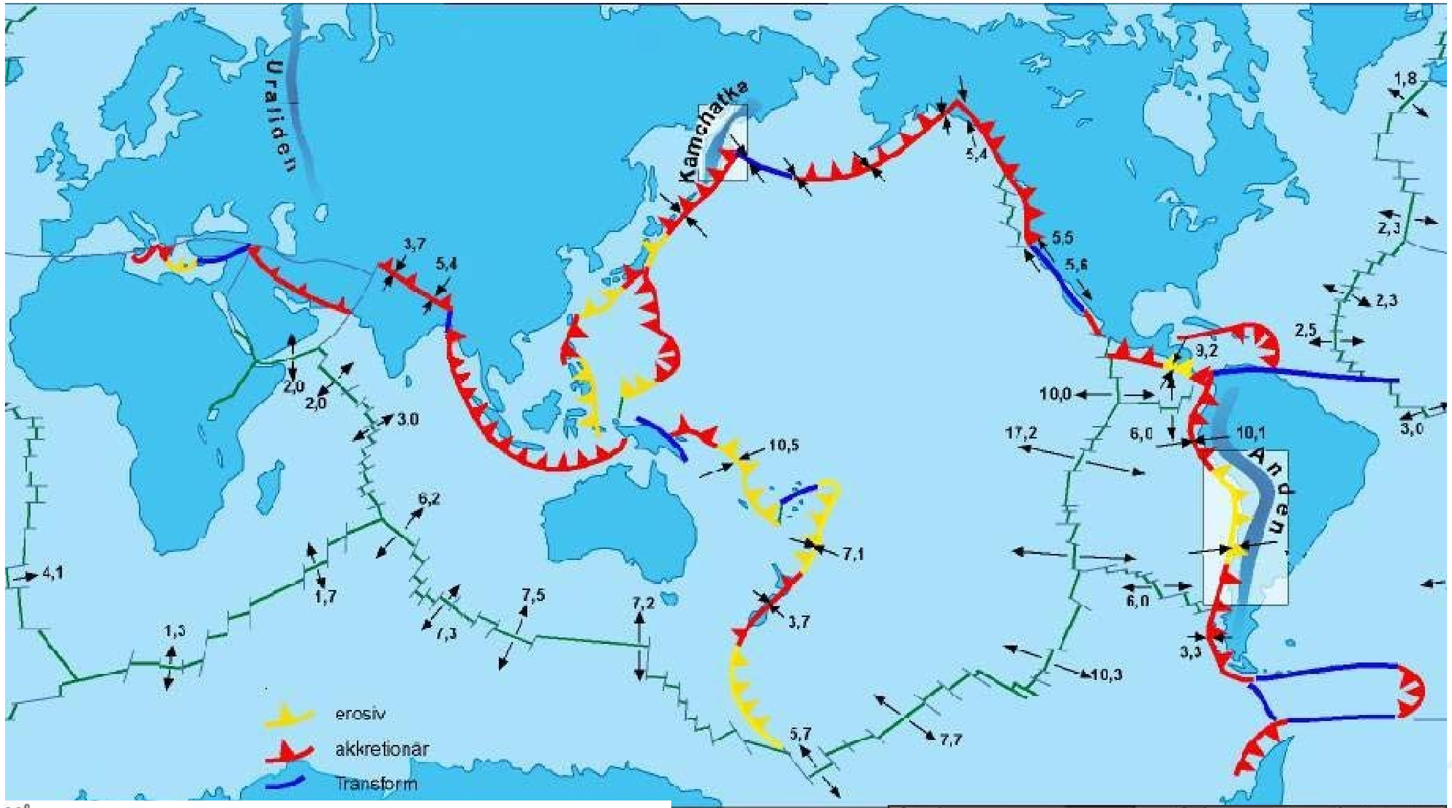
Deterministic Tsunami Hazard Modelling

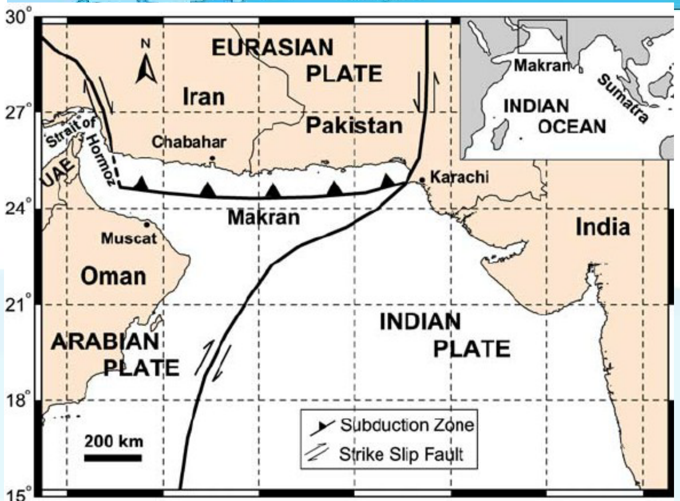


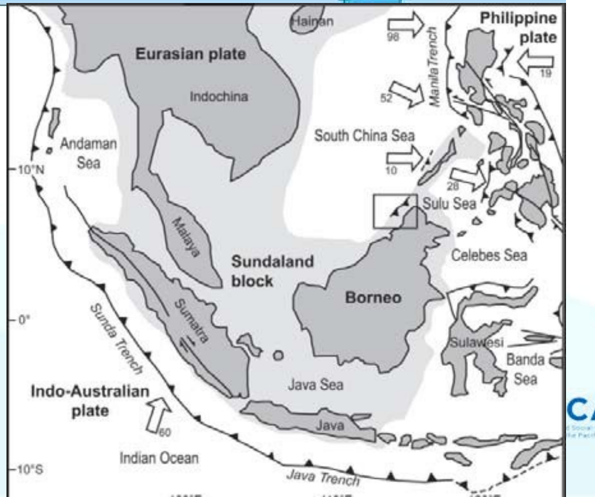
Probabilistic Tsunami Hazard Modelling (PTHM)

- Identification of tsunamigenic sources
- Choose Methodology
  - Historical data
  - Deterministic Tsunami Hazard (scenario) Modeling
  - Probabilistic Tsunami Hazard Modelling
- Model tsunami propagation & onshore Inundation
- Aggregrate numerical results
- Develop tsunami hazard maps

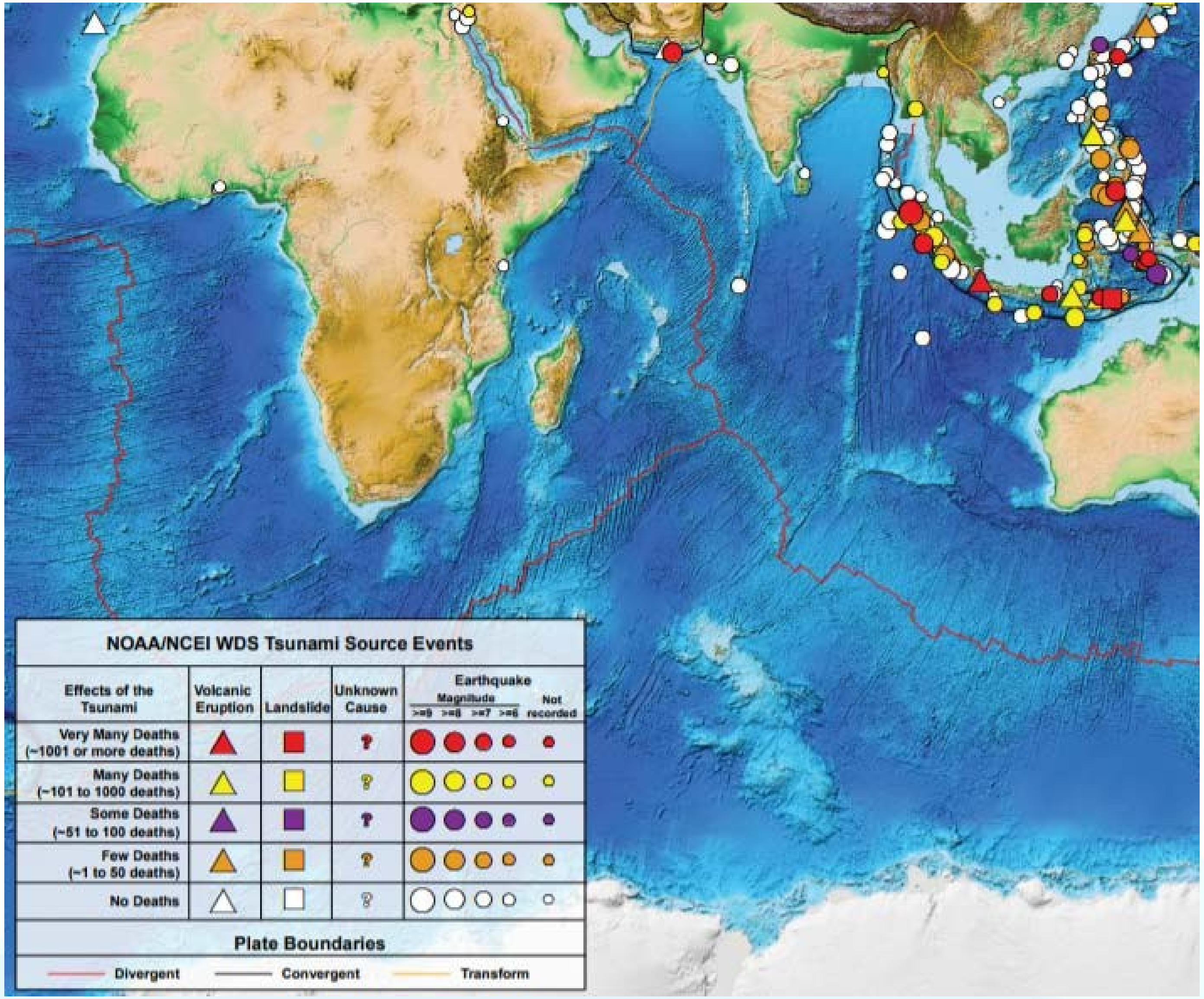
Subduction Zones







Tsunami Sources (NGDC/NOAA)



1881 Nicobar Islands
1883 Krakatoa
1941 Andaman Islands
1945 Makran
1977 Sumba
2004 Indian Ocean

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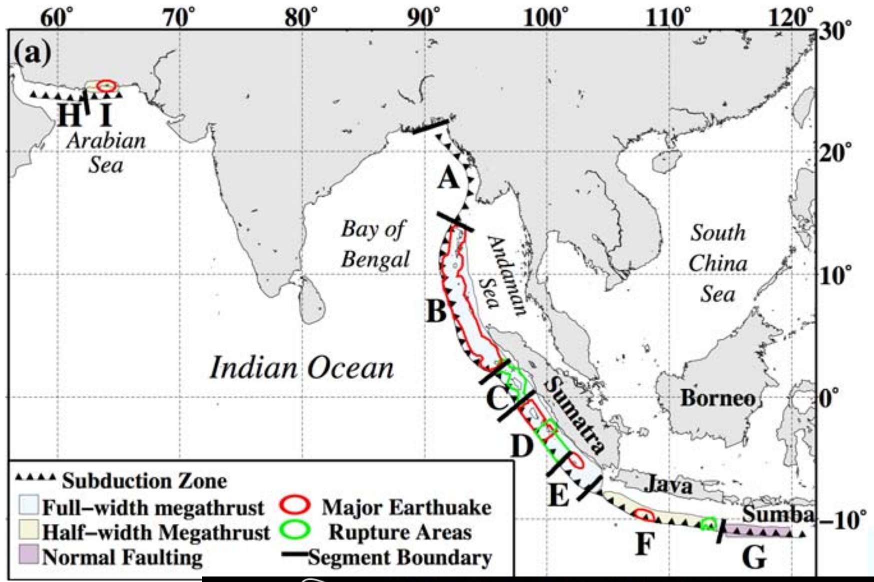
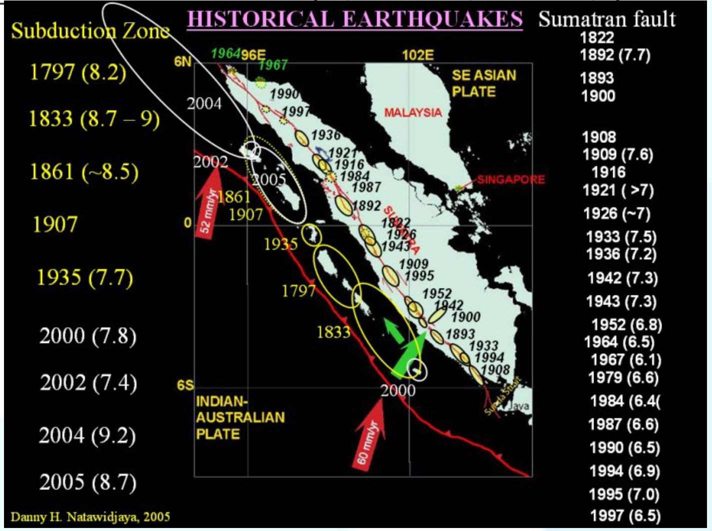
Sources of Tsunami Hazard in the Indian Ocean





800 kilometers across the North Arabian sea
Occurrence of Mw 8.1 earthquake in 1945 near Pasni

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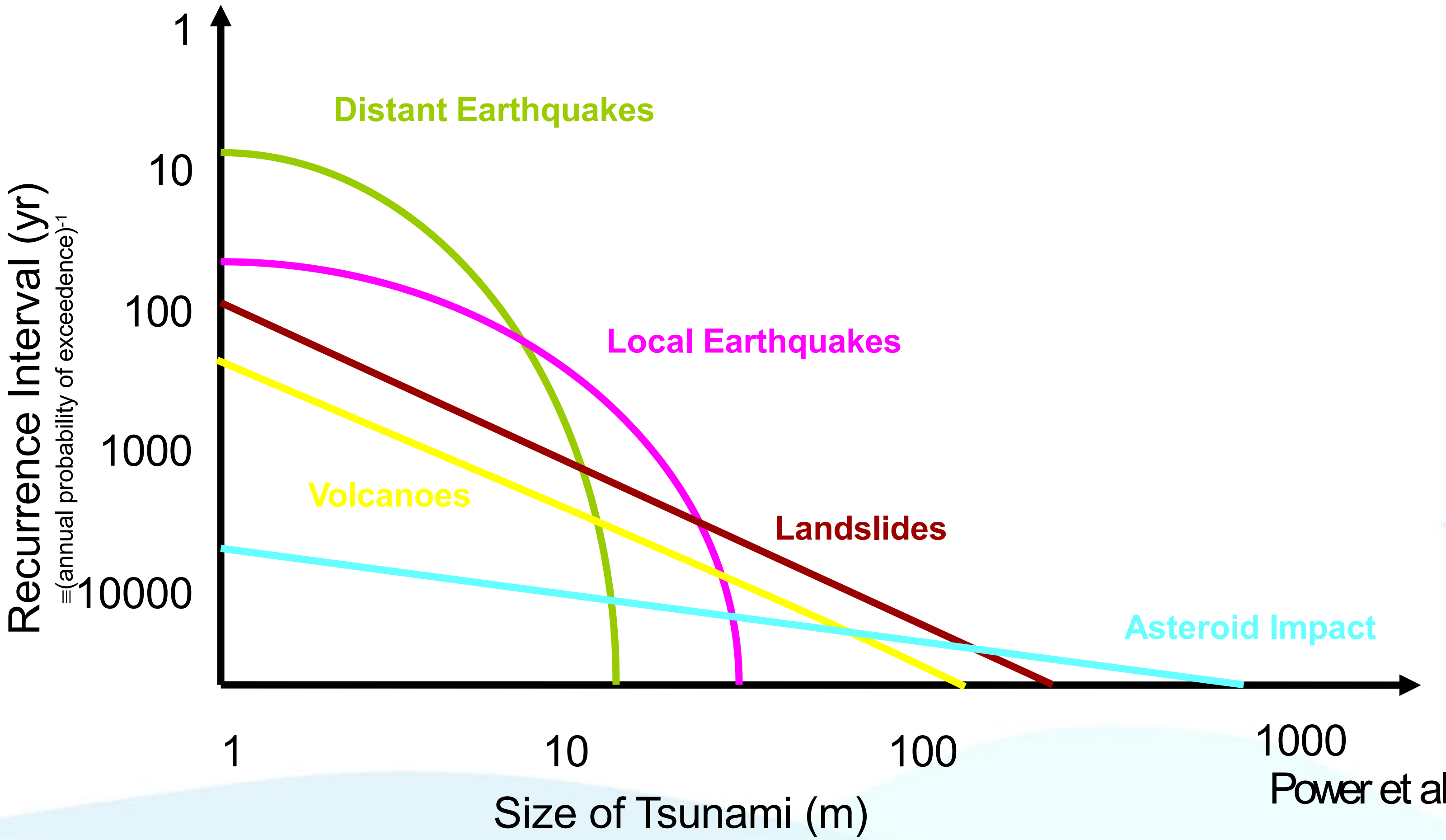
Magnitude/Frequency of tsunami sources

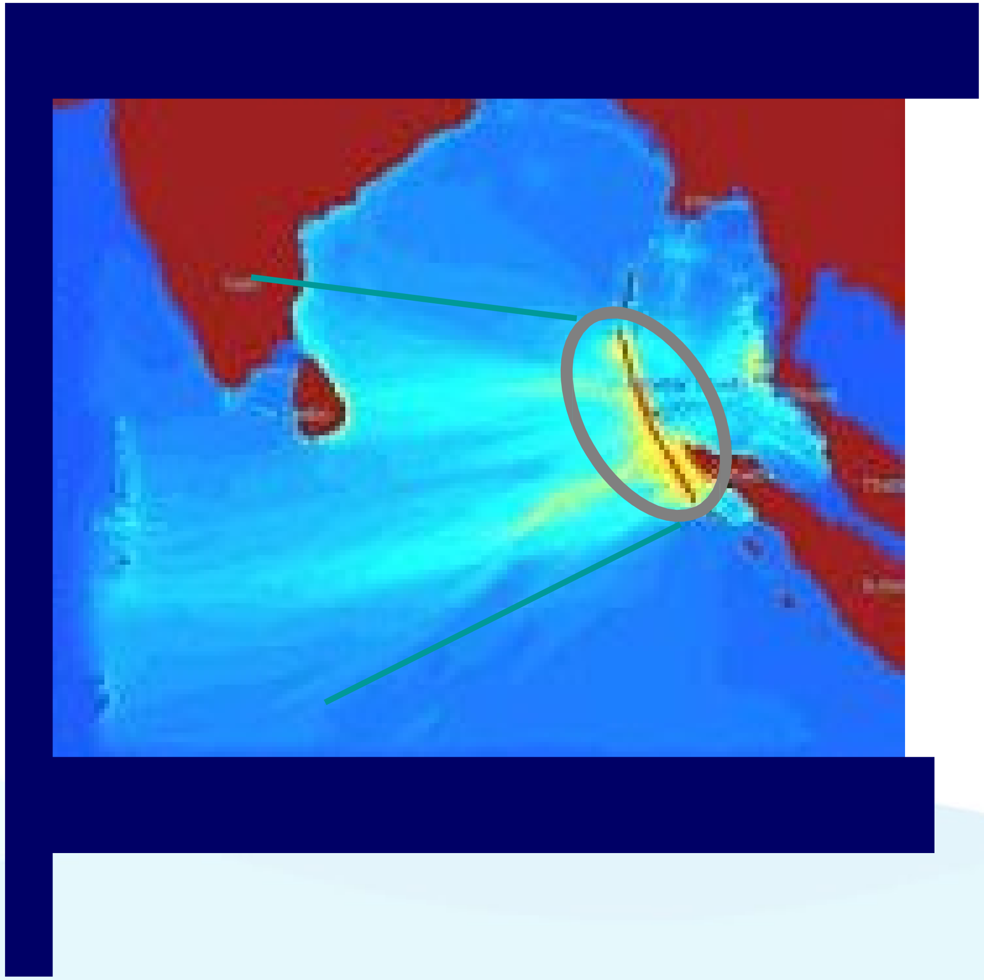


Power et al., 2005

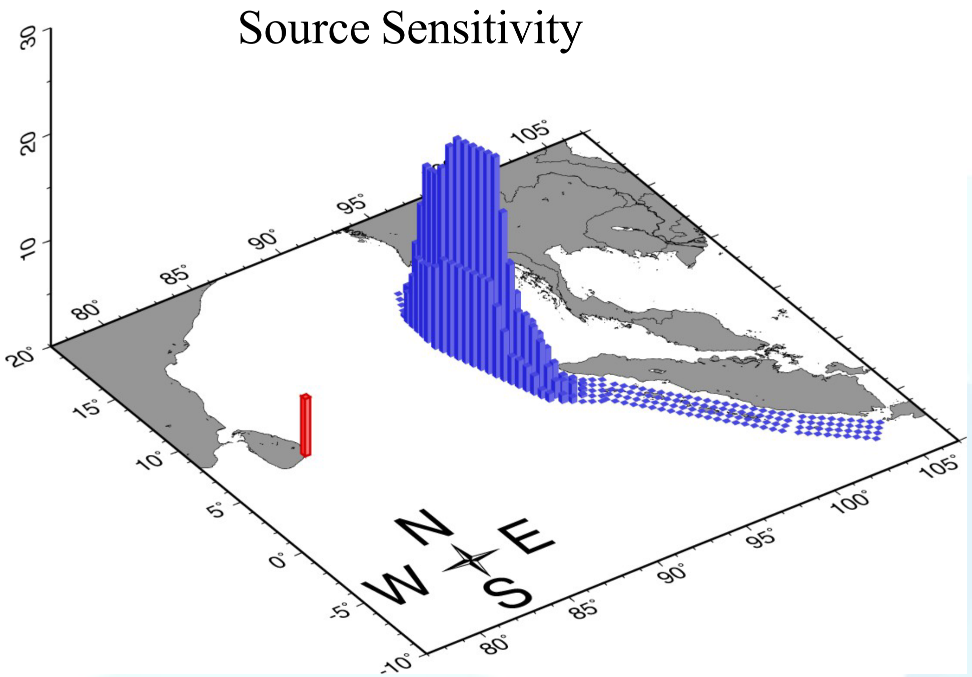
Deterministic Tsunami Hazard Modelling (DTHM)

Probabilistic Tsunami Hazard Modelling (PTHM)

Allows identification of <u>overall exposure</u> from a given hazard source scenario



Allows identification of particular source areas of high exposure <u>for a given site</u>



after Hong Kie Thio

Deterministic Tsunami Hazard (Scenario) Modelling

Questions

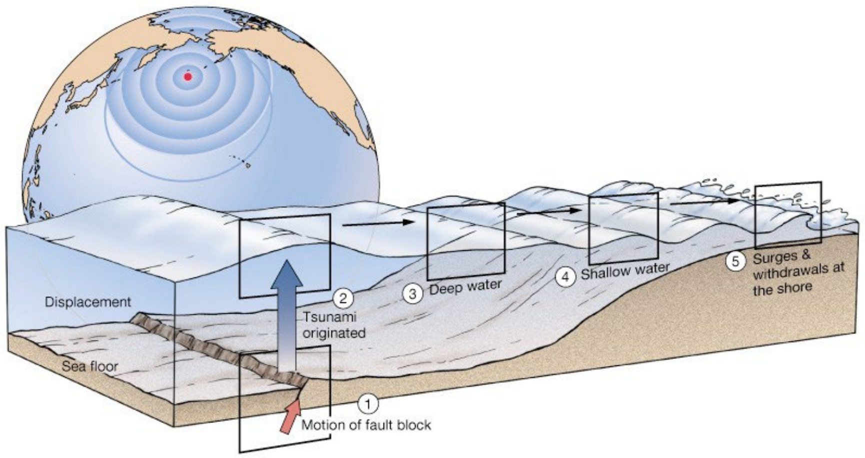
- What is the credible (scientifically defensible) worst-case scenario? – basis for choosing the scenarios
- What is the probability of occurrence of this scenario?
- Were all significant sources included? – tsunamis can cause damages over very large distances
- How many scenarios are needed for a full analysis of the region?

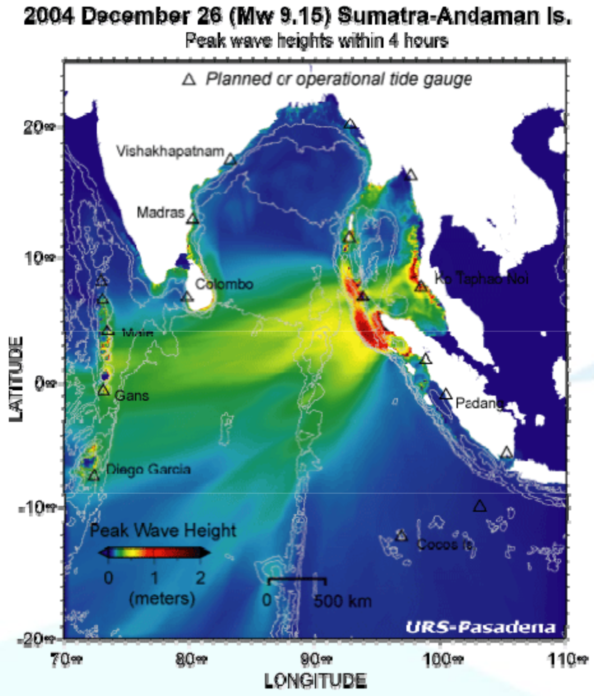
- Develop inundation maps for the above credible worst-case scenario.

Deterministic Tsunami Hazard (scenario) Modeling

Advantage

- Can give very detailed and complete information on the impact of tsunamis on a region - inundation, flow velocity, etc.



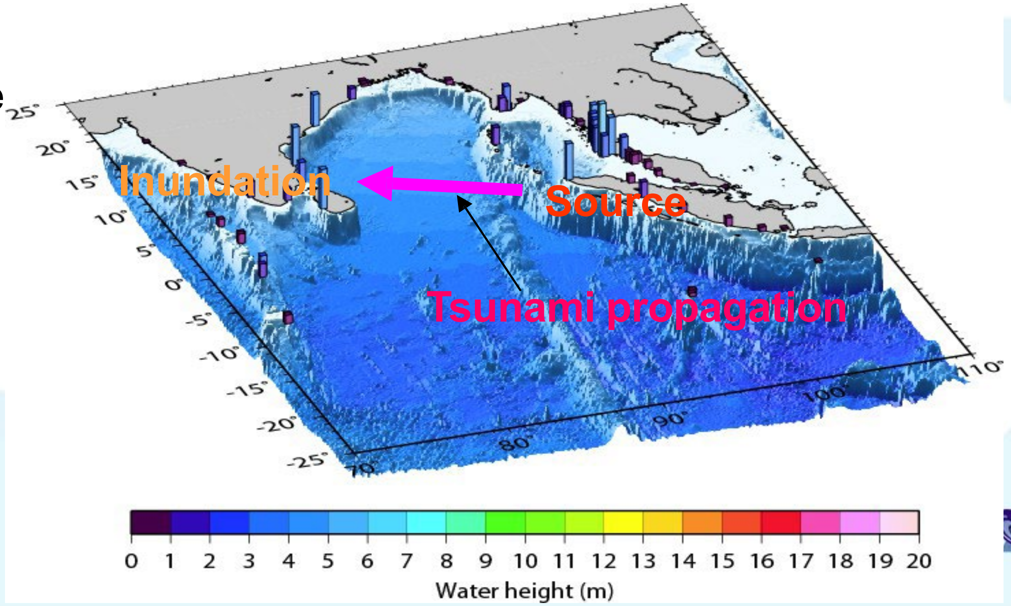


Tsunami Inundation Modelling

- Tsunami inundation is a complex hydrodynamic process which requires a sophisticated numerical model to represent accurately.
- The hydrodynamics can be very sensitive to details of near-shore bathymetry and topography, requiring high-resolution data for accurate modelling.
- Because it is so resource intensive, optimal use should be made of an offshore tsunami hazard assessment to identify the coastlines at greatest risk and the source zones that threaten them.

Source, Propagation and Inundation Models

- **source model** which creates the initial water surface disturbance given the earthquake parameters (Okada's formulation)
    - tsunami **propagation** from its origin to the nearshore coast,
    - tsunami **run-up and inundation** with a moving boundary.
    - Solves the **linear/non-linear shallow-water equations**.



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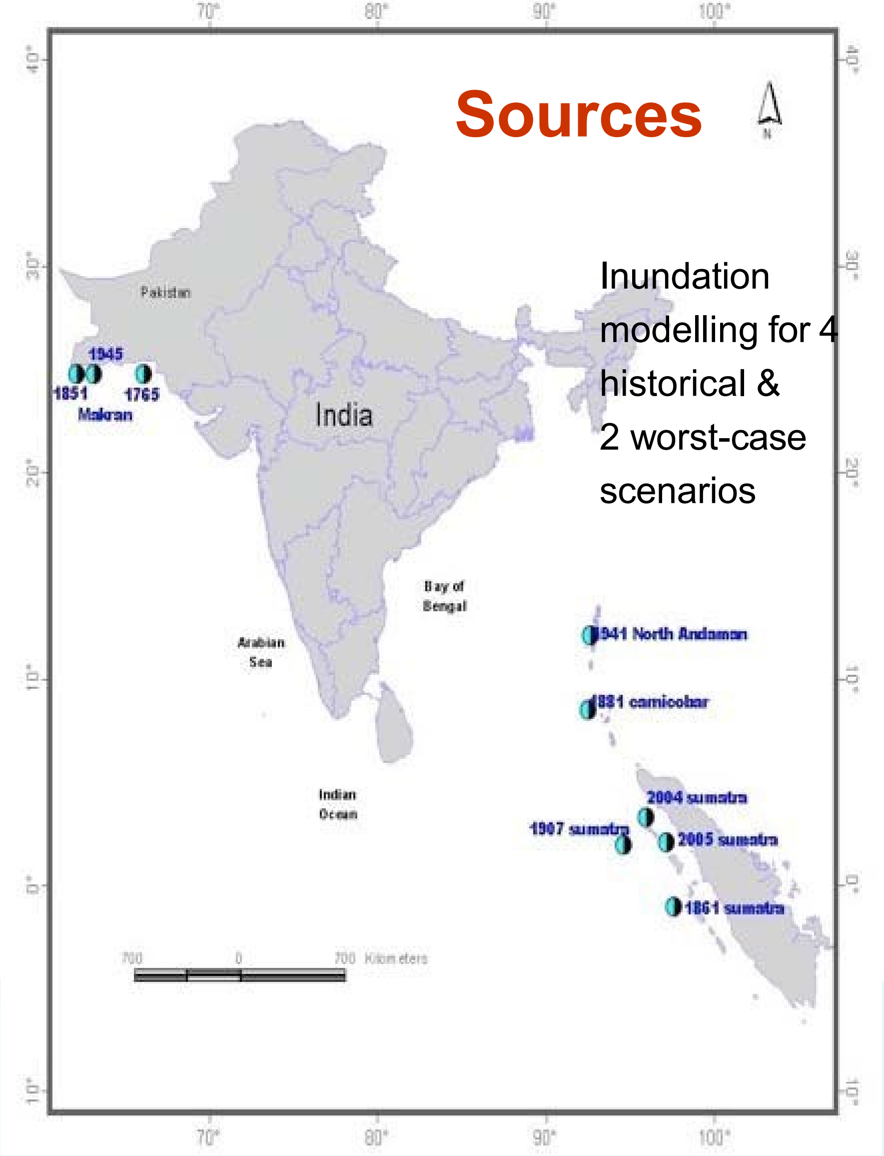
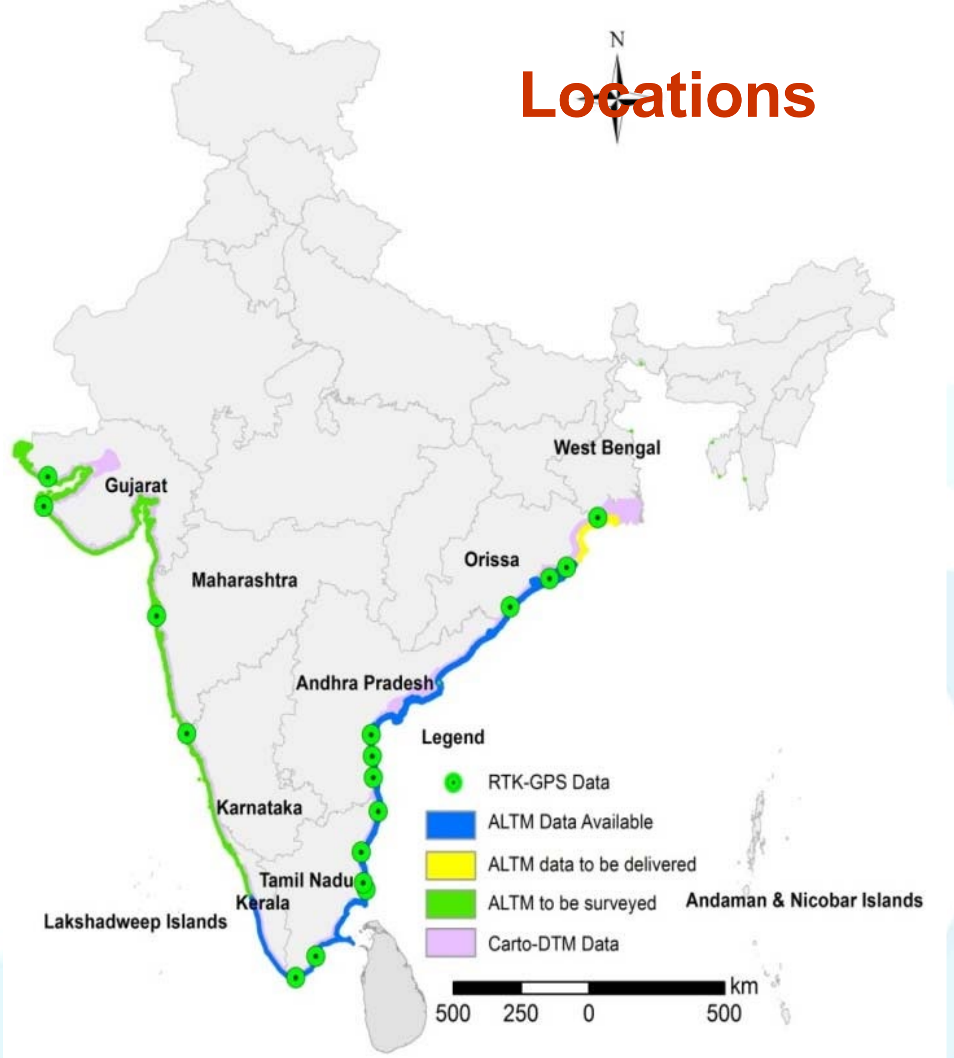
Selection of Credible Worst-case Source Scenario and Coastal Locations for Modelling – Case study of India



Inundation modelling for 4 historical & 2 worst-case scenarios



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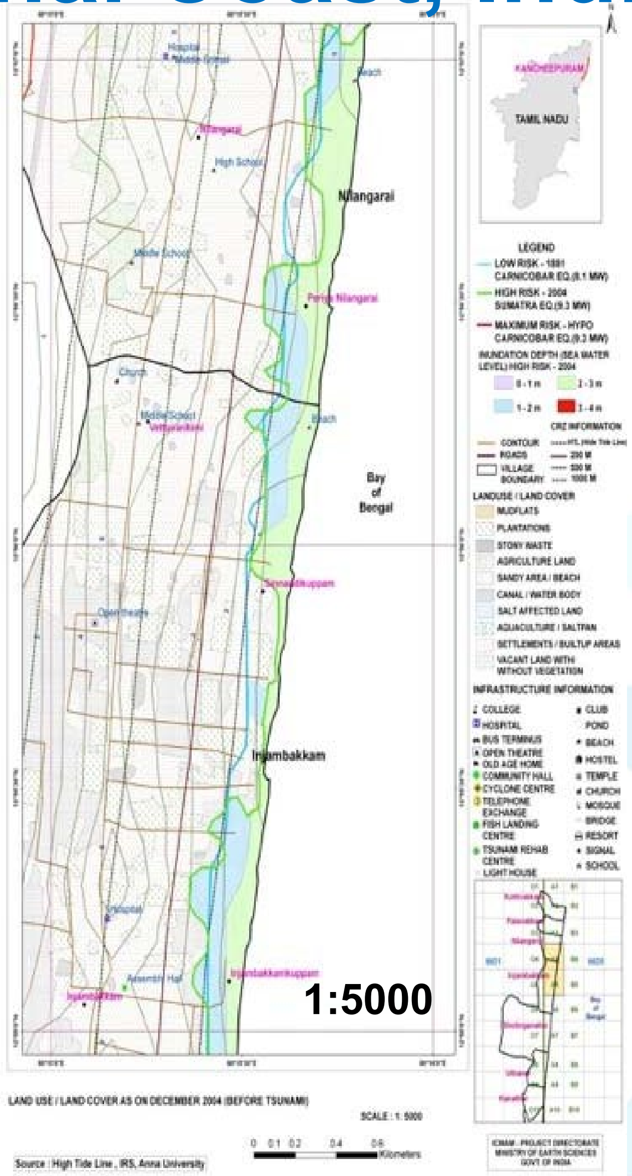
Courtesy: ITEWC

Tsunami Hazard Map of Chennai Coast, India

- To draw up evacuation plans
- To provide education on disaster mitigation
- To increase public awareness of disaster mitigation
- To enhance communication with residents regarding disaster risks
- To build strong and more resilient communities against disasters.



Courtesy: ITEWC

Probabilistic Tsunami Hazard Analysis

- Analogous to probabilistic seismic hazard analysis (PSHA), e.g. Global seismic hazard map
- Use sub fault Green's function summation as proxy for traditional attenuation relations
- Source recurrence model identical to PSHA models, but need to consider submarine landslide sources

Probabilistic Tsunami Hazard Assessment (PTHA)

Probabilistic Tsunami Hazard Assessment (PTHA) involves a range of probable tsunamigenic scenarios and numerical modelling of each scenario to obtain the spatial distribution of near-shore tsunami amplitude and/or onshore inundation for a given area of interest.

Probabilistic Tsunami Hazard Modeling

Advantages

- Integration over thousands of scenarios
- Uncertainties are included
- Likelihood of exceeding certain wave parameters (Wave height, velocity, etc.)

Disadvantages

- Computational load restricts us to simple propagation models, i.e. no run up

Probabilistic Tsunami Hazard Assessment (PTHA)

Like PSHA, PTHA assumes the probability of exceedance of a certain offshore tsunami height h_{crit} follows a Poisson distribution:

$$P^i(h \geq h_{crit}) = 1 - \exp\left(-\phi^i(h_{crit})t\right)$$

where $Ø^i(h_{crit})$, the average annual frequency of exceeding h_{crit}, is the sum of contributions from each source zone j:

$$\phi^i(h_{crit}) = \sum_j N_j(M \geq M^i_{crit})$$

N_j is the annul number of earthquakes in zone j of magnitude greater than M_{crit}, which causes a tsunami of offshore height h_{crit} at location i.

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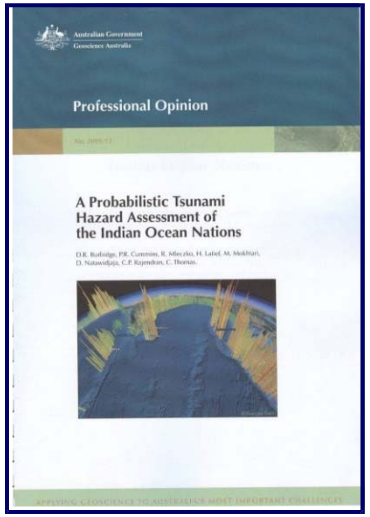
Advantages of Green's function based PTHA

- Great flexibility in choosing hazard parameters such as wave height, downdraft, flow velocity, spectral amplitude (resonance)

- Easily extendable to multi variate hazard (e.g. joint probability of inundation height and duration of inundation)

A PTHA Study for the Indian Ocean



A Probabilistic Tsunami Hazard Assessment of the Indian Ocean Nations

Sept 2009

Team Leader- Dr Phil Cummins

AusAID-funded collaboration between geotechnical agencies of Indian Ocean countries:

- Geoscience Australia
- Indonesian Institute of Sciences/Bandung Institute of Technology
- Centre for Earth Sciences, Indian Institute of Science
- International Institute of Earthquake Engineering and Seismology, Iran
- Implemented by Geo Science Australia as an activity of Working Group on Risk assessment of IOTWS

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Main Steps in PHTA

1. Determine the earthquake source zones to be included in the study

2. For each source zone, determine the possible characteristics of the earthquakes that could occur in that source zone, and the probability of each such earthquake occur-ring. Use this to assemble a large catalogue of possible (or synthetic) earthquakes.

3. Simulate the tsunami from each synthethic earthquake and estimate the maximum tsunami amplitudes that result from each tsunami at a number of selected locations (called model output points) near each Indian Ocean nation.

4. Combine these results to calculate the probability a given maximum tsunami amplitudes could be exceeded per year.

Outputs

- **Hazard Curves**: These describe the relationship between the return period and the maximum tsunami amplitude for a particular model output point.
- **Maximum Amplitude Maps**: The maximum tsunami amplitude that will be exceeded at a given return period for every model output point in a region. A different map for the region can be drawn for each return period.
- **Probability of Exceedance Maps:** For a given amplitude, these maps show the annual probability of that amplitude being exceeded at each model output point in a region. A different map can be drawn for each amplitude for that region.
- **Deaggregated Hazard Maps**: These indicate the relative contribution of different source zones to the hazard at a single location. A different map will be obtained for every choice of model output point (and for different return periods), and so there are a great many possible deaggregated hazard maps that may be drawn for any given region.
- **National Weighted Deaggregated Hazard Maps:** These give an indication of the source of the hazard to a nation or region as a whole, and are are not specific to a particular offshore location. The national weighted deaggregated hazard maps provide a convenient summary of the source of hazard over a region.

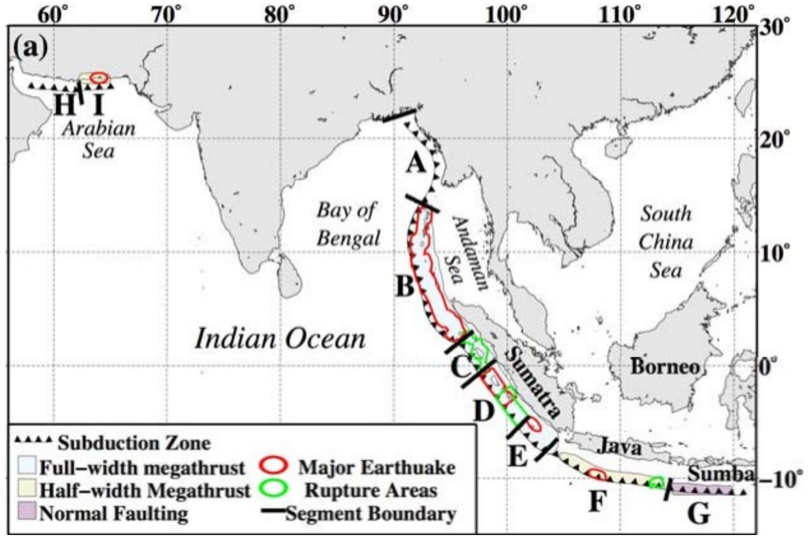
A Probabilistic Tsunami Hazard Assessment for the Indian Ocean

- Probabilistic Tsunami Hazard Assessment (PTHA) methodology
  - Only subduction zone earthquake sources of tsunami considered
  - Hazard expressed as offshore tsunami amplitude

- Uncertainty must express profound lack of knowledge of recurrence of tsunamigenic Indian Ocean earthquakes - 2 hazard maps:
  - Low-hazard end member, based on only those earthquake sources of tsunami for which there is definite evidence
  - High-hazard end member, based on all potential subduction zone earthquake sources, including hypothetical ones for which there is no historical or geological evidence
  - Difference expresses uncertainty, with actual hazard lying between the two end members

Low-Hazard Source Zonation

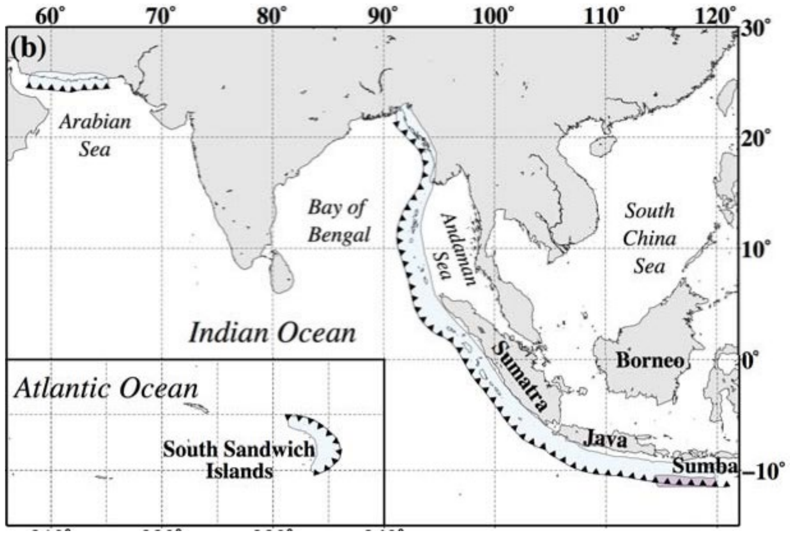
based on only those earthquake sources of tsunami for which there is definite evidence



Each subduction zone source characterized by historical tsunamigenic earthquake occurrence only

High-Hazard Source Zonation

based on all potential subduction zone earthquake sources, including hypothetical ones for which there is no historical or geological evidence



All potential subduction zones can rupture at full width, limited by lesser of magnitude 9.5 events or full subduction zone length

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Subduction Zone	Segment	Maximum Magnitude (Mw)		
		Historical	Low Hazard	High Hazard
Andaman-Sunda Arc	A	unknown (1762[1])	0.0	9.5
	B	9.2 (1881[2], 2004[3])	9.2	
	C	8.7 (1861,2005[4])	8.7	
	D	9.1 (1797,1833,2007[5])	9.1	
	E	7.6 (2000[5])	7.6	
	F	7.8 (1994[7],2006[8])	7.8	
	G	none	0.0	
Makran	H	unknown (1483[8])	0.0	9.1
	I	8.1 (1945[9])	8.2	
South Sandwich		none	0.0	9.0

Table 2: Summary of megthrust earthquake tsunami source zones used in the low-hazard and high-hazard maps. The three subduction zones considered are shown, along with the segmentation that was used for the low-hazard maps (see Fig. 5a). The maximum magnitude of the historical earthquakes listed in brackexts is listed in the third column. The maximum magnitudes used to generate the low-hazard and high-hazard assessments are shown in columns four and five. Where the maximum magnitude for historical earthquakes is listed as 'unknown' that indicates that a large (possibly megathrust) earthquake occurred, but its magnitude is unknown. By contrast 'none' indicates that there is no known historical occurrence of a megathrust earthquake large enough to generate a destructive tsunami. The years of historical earthquakes are indicated in parentheses with superscripts to indicate the following references: [1] Cummins (2007), [2] Ortiz and Bilham (2003), [3] Stein

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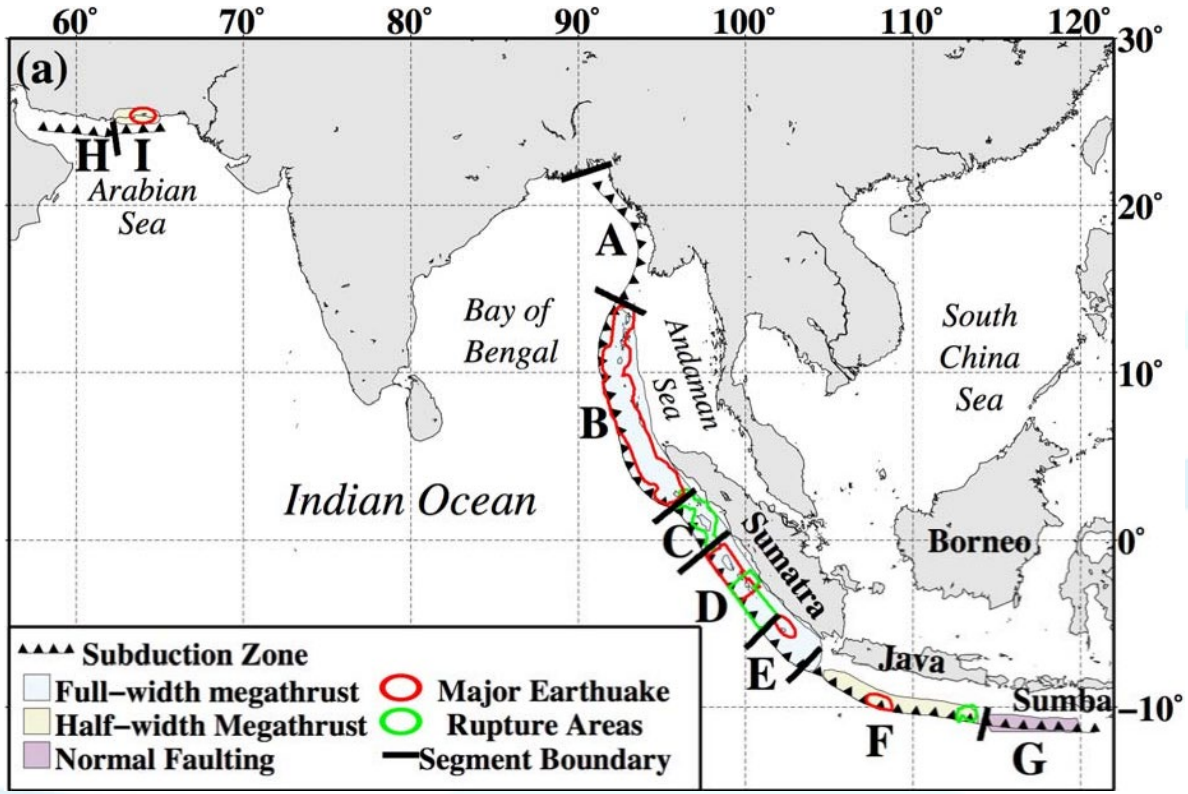
Low-Hazard Source Zonation

Each subduction zone source characterized by historical tsunamigenic earthquake occurrence only

- Dominated by Andaman-northern Sumatra full width megathrust (2004 eq)
- Central Sumatra - Java: half and full width megathrust segments (2007, 1994, 2006, etc eqs)
- Makran half-width megathrust in eastern segment only (1945 eq)



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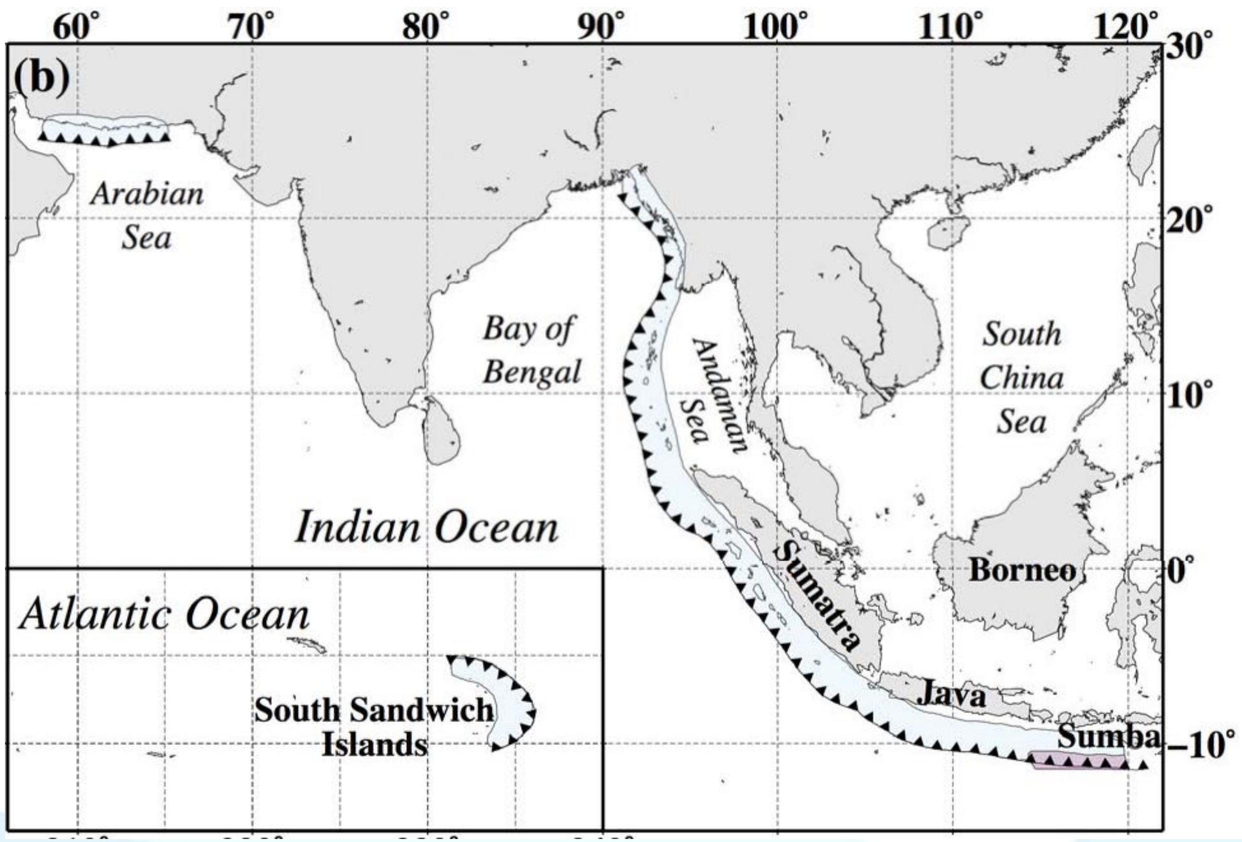
High-Hazard Source Zonation

All potential subduction zones can rupture at full width, limited by lesser of magnitude 9.5 events or full subduction zone length

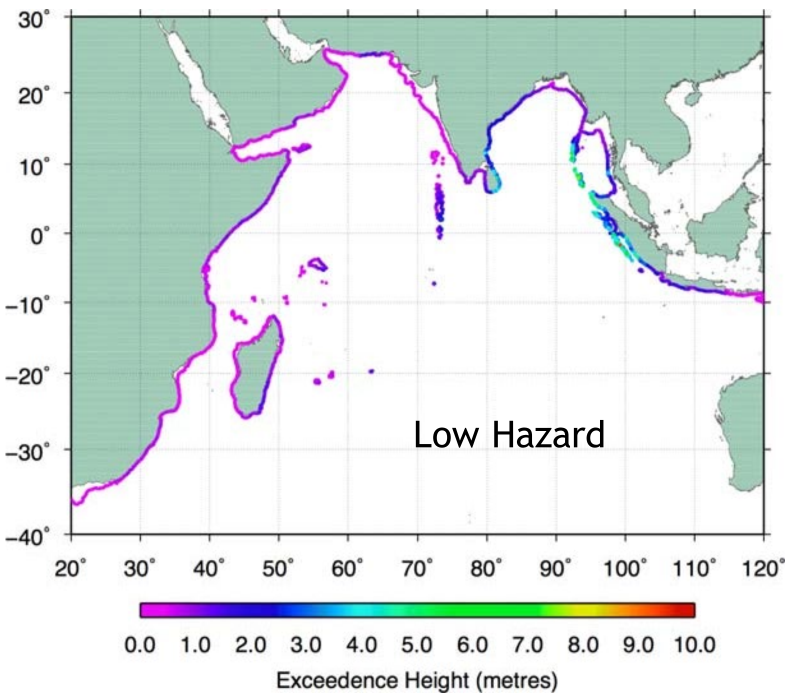
- Sunda Arc from Myanmar to Sumba can rupture in magnitude 9.5 eqs

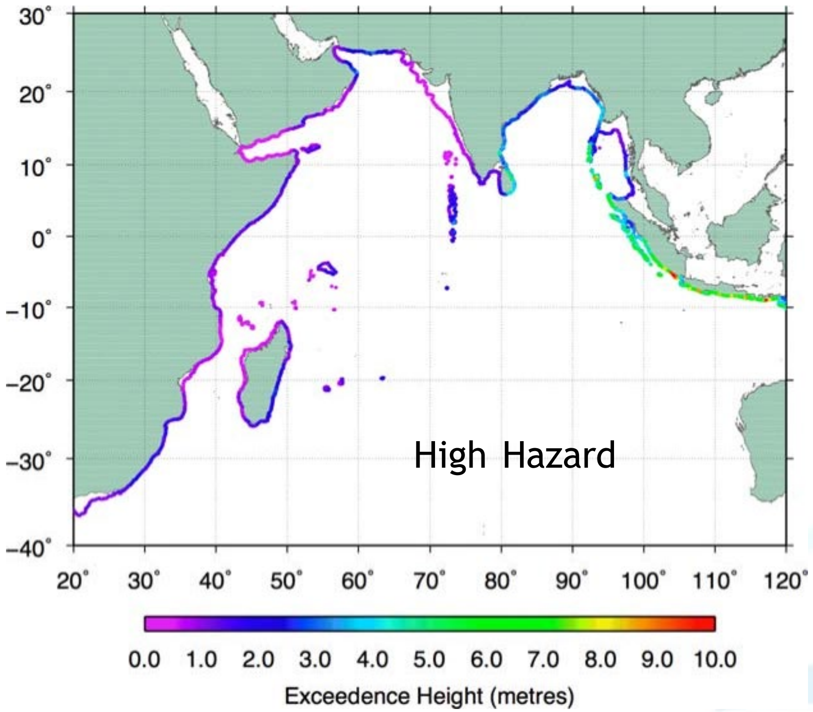
- Makran can rupture
- from west to east in mangnitude 9 eq.

- South Sandwich Arc can rupture in magnitude 9 eq



Indian Ocean Results for 2000-year Return Period



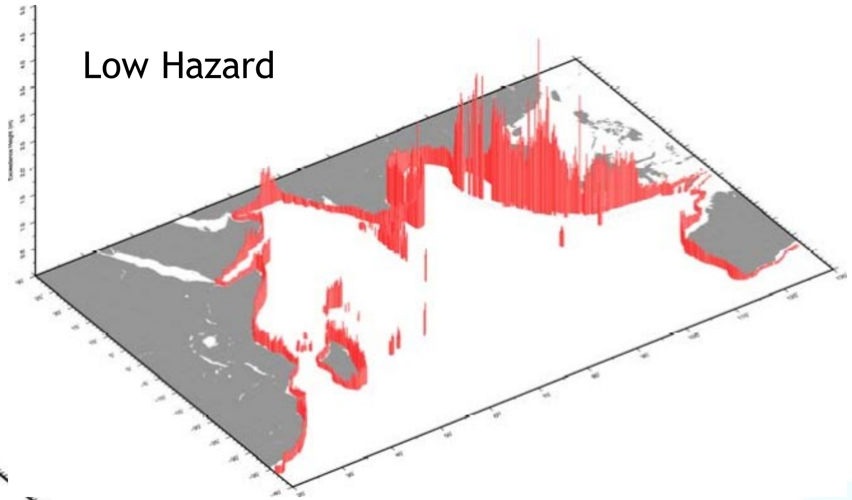


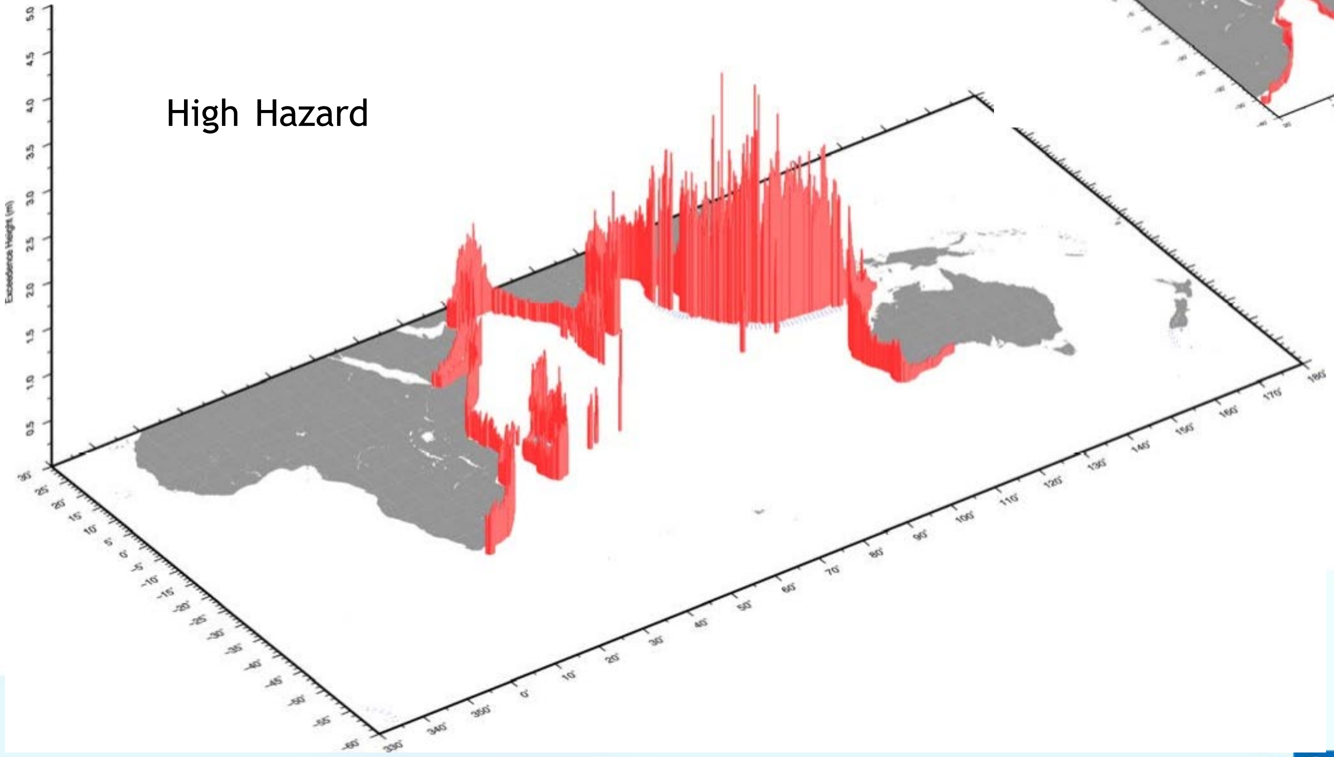
Relative offshore tsunami heights for low-hazard case reflect mainly impacts from 2004 IOT, 1945 Makran tsunami, and other events off Sumatra and Java

Offshore heights for high-hazard case at least twice as large on most coastlines; much larger on coastlines affected by additonal source zones (e.g., Burma)

Indian Ocean Results for 2000-year Return Period

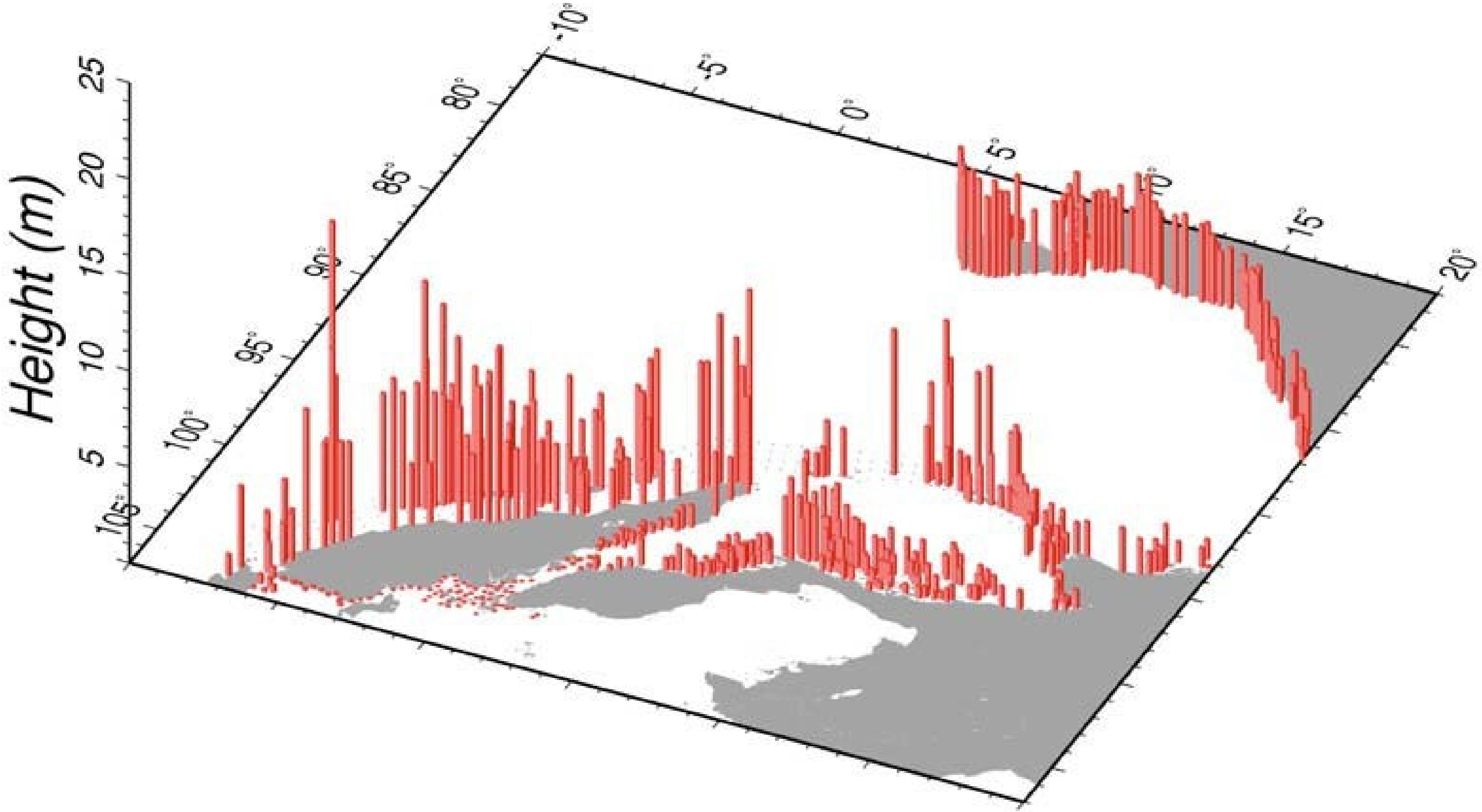
Relative offshore tsunami heights for low-hazard case reflect mainly impacts from 2004 IOT, 1945 Makran tsunami, and other events off Sumatra and Java





Offshore heights for high-hazard case at least twice as large on most coastlines; much larger on coastlines affected by additonal source zones (e.g., Burma)

Hazard maps: 475 Yr Tsunami Exceedance Heights ("500 yr event") for the NE Indian Ocean Due to Earthquakes Along the Sumatran- Andaman Subduction Zone



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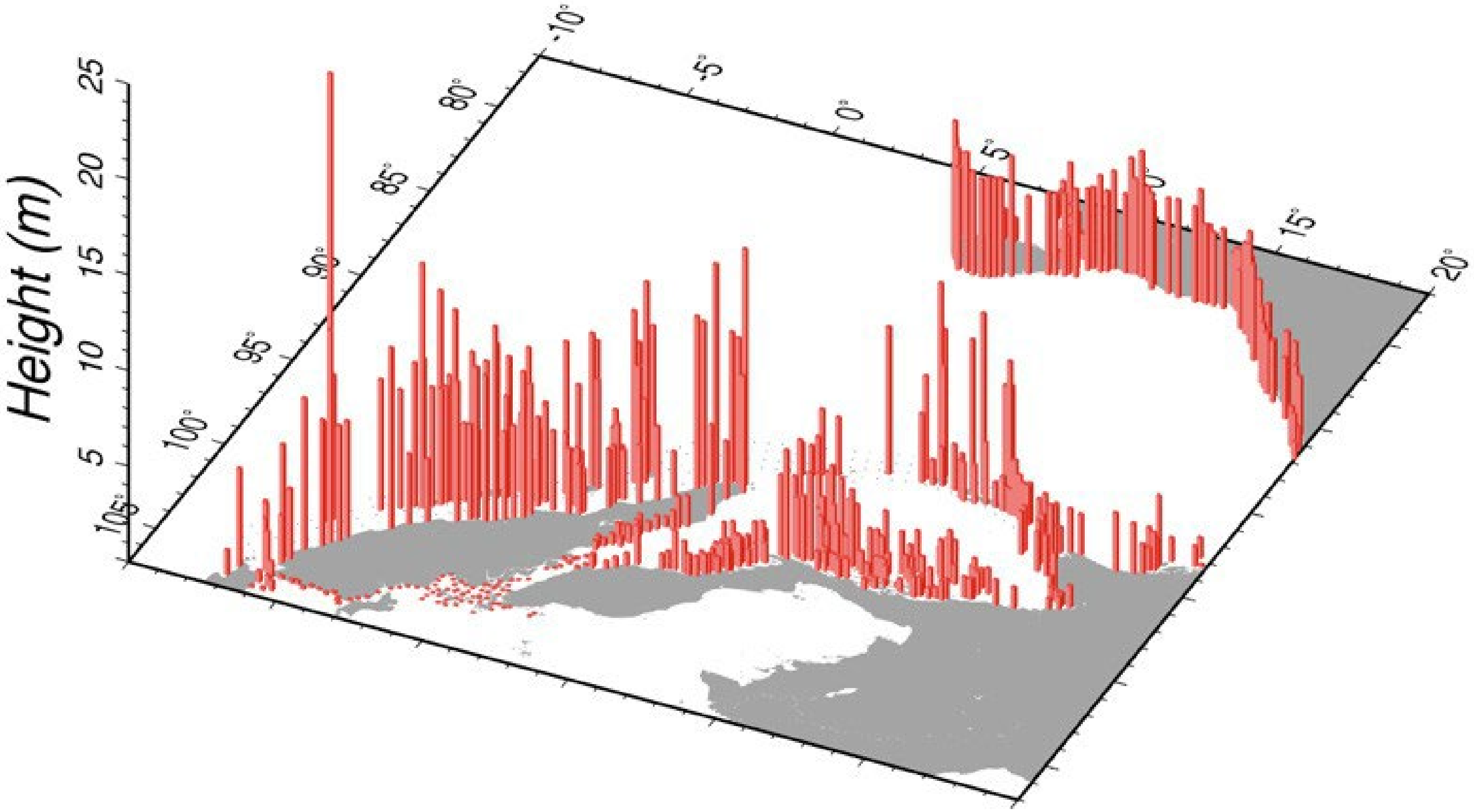
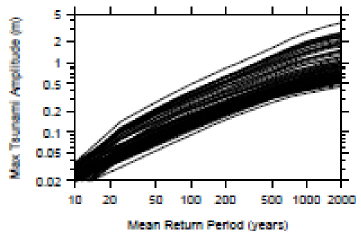
Hazard maps: 975 Yr Tsunami Exceedance Heights for the NE Indian Ocean due to Earthquakes Along the Sumatran-Andaman Subduction Zone

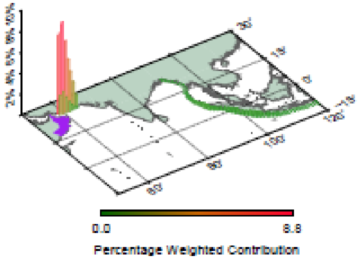


5.28 Oman (high hazard)

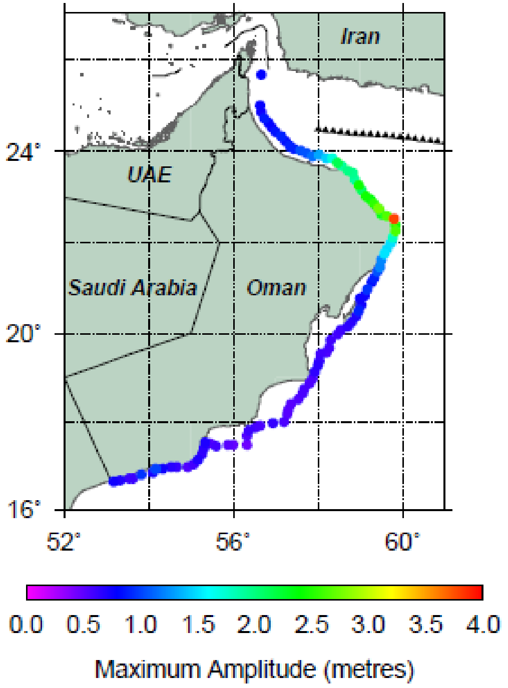
In the high hazard assessment the hazard off northeast Oman which directly faces the western Makran is significantly larger than any other section of the Omani coast (Figure 43(c)). One isolated point has a maximum exceedence amplitude at 2000 years of 5m, however since that point is isolated it should be treated with caution (Figure 43(c)). The hazard for the rest of the Omani coast ranges from 0.5m to 3.8m (Figure 43(a)). In this high hazard assessment the hazard at the 2000 year return period is dominated by the Western Makran, with a relatively small contribution from Sumatra (Figure 43(b)).



(a)



(b)



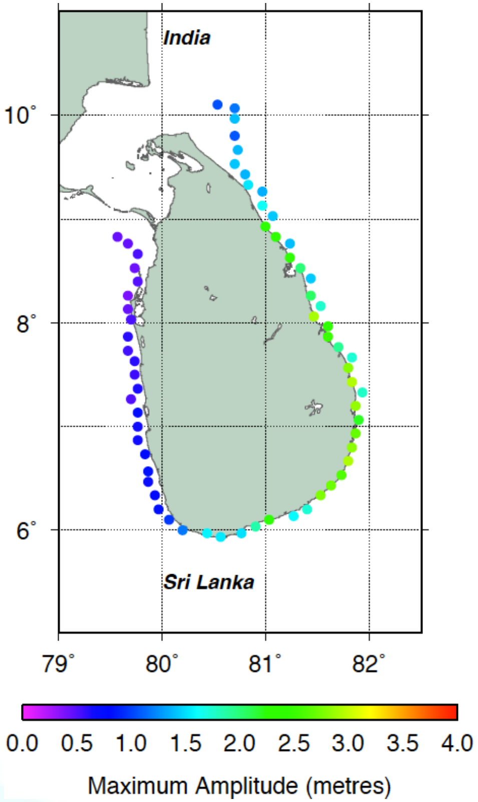
(c)

Figure 43: Oman:- (a) Hazard curves for all model output points. (b) National weighted deaggregated hazard. (c) Maximum amplitude at a 2000 year return period for all model output points.

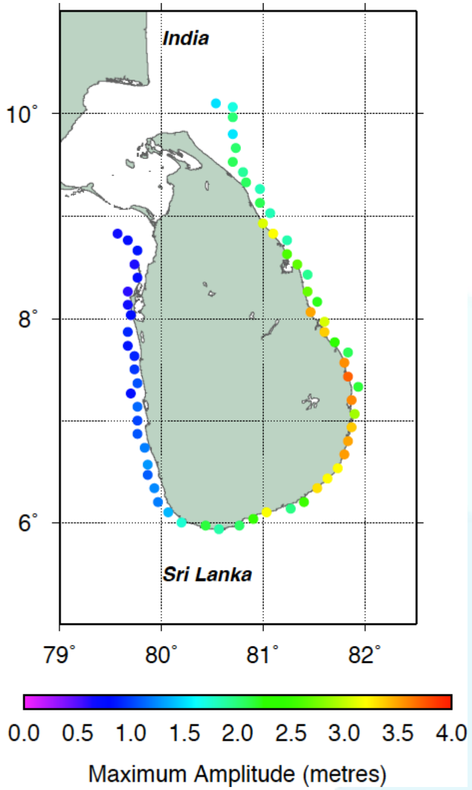
Example of Offshore Tsunami Hazard for Sri Lanka

- Low hazard end-member

High hazard end-member

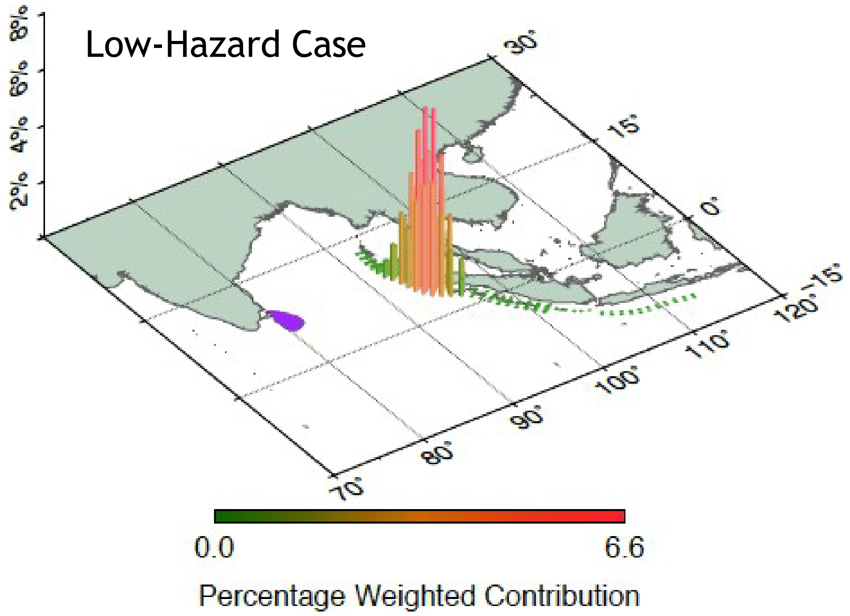


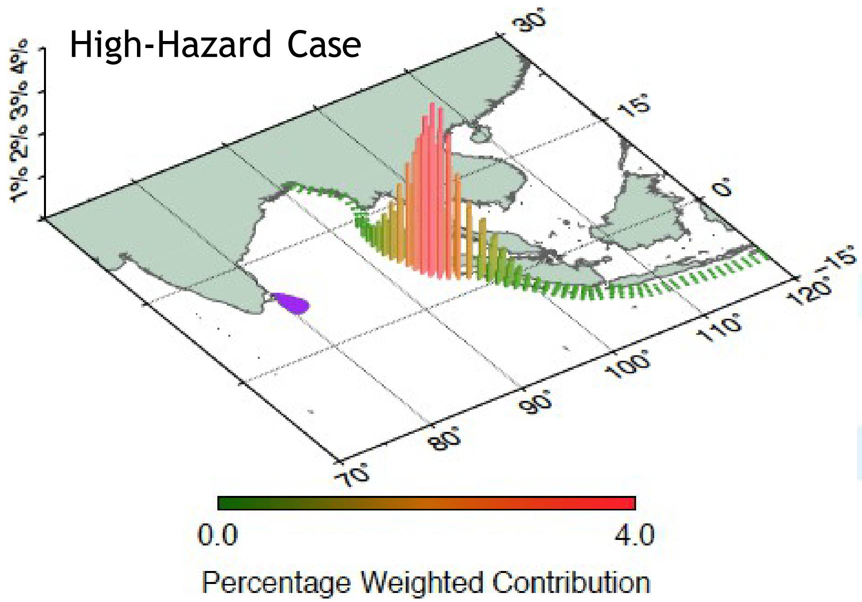
- For Sri Lanka, the low-hazard and high- hazard maps are very similar in character, with hazard maximum along the east coast and the high hazard case greater than the low by about 30%.



Example: Deaggregated Tsunami Hazard for Sri Lanka

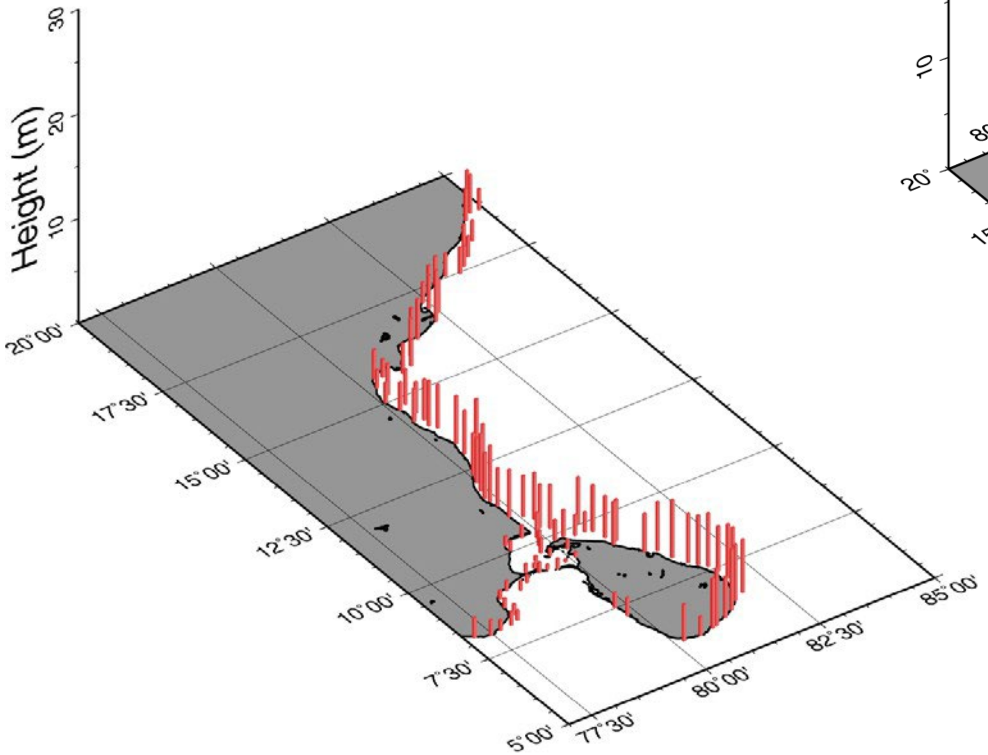
Deaggregated hazard displays the relative contribution of different sources to the tsunami hazard at a particular location.

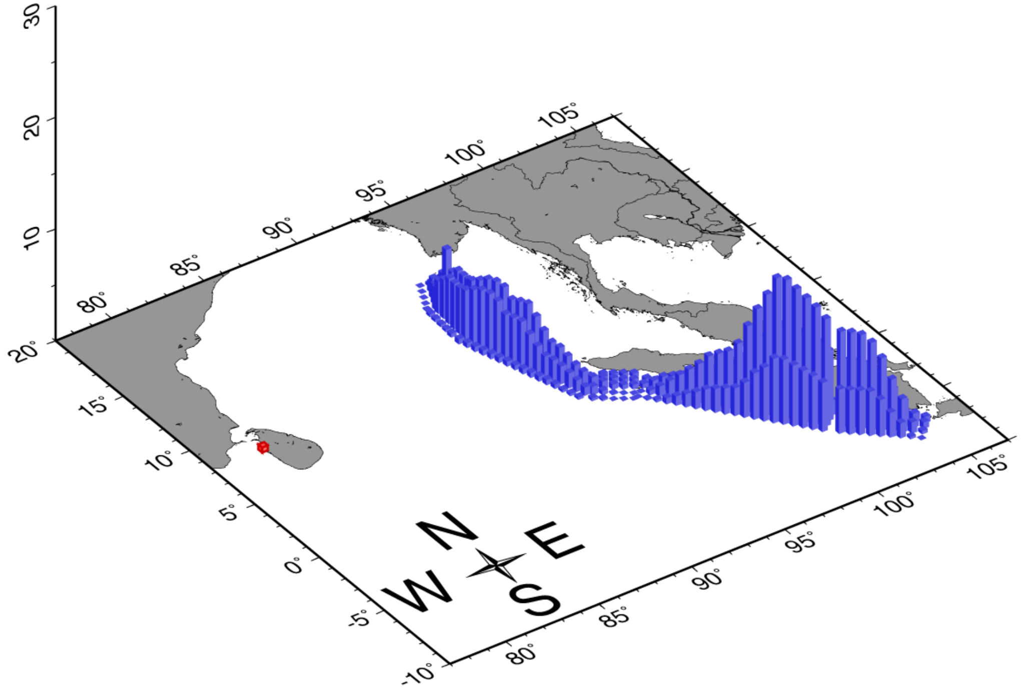




Both Low- and High-hazard cases show that tsunami hazard in Sri Lanka is dominated by events in North-Sumatra/Nicobar Islands. Probably, this means that the 2004 IOT was the 'worst-case' scenario for Sri Lanka..

Tsunami hazard and source sensitivity for India and Sri Lanka





Allows identification of particular source areas of high vulnerability for a site

Indian Ocean PTHA Conclusions

Very large coastal populations in the Indian Ocean are potentially at risk from local tsunamis (for which warning may be problematic).

- Several nations, particularly those in the northeast of the Indian Ocean, have a very high tsunami hazard, particularly Indonesia. These nations are usually close to the Sunda Arc subduction zone or are perpendicular to it (eg Indonesia, India and Sri Lanka). These were also the nations most affected by the 2004 Indian Ocean tsunami.
- The nations located northwest of the Indian Ocean (eg Iran, Pakistan and UAE) have a more moderate hazard than Indonesia. The hazard here is controlled by the activity of the Makran subduction zone, which also has an uncertain maximum magnitude.
- For the islands in the central to western Indian Ocean potentially dangerous tsunami can come from either the Makran or the western Sunda Arc zone. The offshore hazard is somewhat lower for these islands because they are significant further from the tsunami source.
- For nations in the southwest Indian Ocean (eg eastern South Africa, Madagascar, Mozambique and Reunion) some of the 2000 year hazard also comes from the South Sandwich zone in the southern Atlantic as well as from the Sunda Arc. The hazard for these nations is otherwise moderate.

The IO- PTHA developed here provides a useful basis for more detailed, community-level studies, by identifying populations at risk and the sources that threaten them.

This IO- PTHA is only a small step towards preparing Indian Ocean coastal communities for the tsunami threat they may face. Much more work is needed.

Community scale hazard and risk assessments that consider shoaling, inundation, and coastal populations/infrastructure.

High-Hazard vs. Low Hazard Assessment - Which is Right?

- Both are not conclusive!

- The high-hazard assessment over-estimates and the low hazard assessment underestimates the hazard - by design.
- The question of which assessment to use depends on the question asked - e.g., is a conservative, “worst-case” to be used for planning, or do resources limit consideration do those events we know can occur?

- Emergency managers/planners should seek expert advice

- Future versions of the hazard map will likely weight low- vs. high- hazard assessments using a logic tree approach.

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Is your coastline at risk? Important Questions

- Which of your coastal communities face a threat from tsunamis significant enough to call for inundation modelling, and which tsunami scenarios would you choose for such modelling?
- Where is the tsunami hazard along your coast significant?
- How uncertain is it - i.e., how much do low and high hazard assessments differ?
- What are the important source zones?
- Is the main tsunami threat due to local, regional, or distant source zones?
- What is the main source of uncertainty?

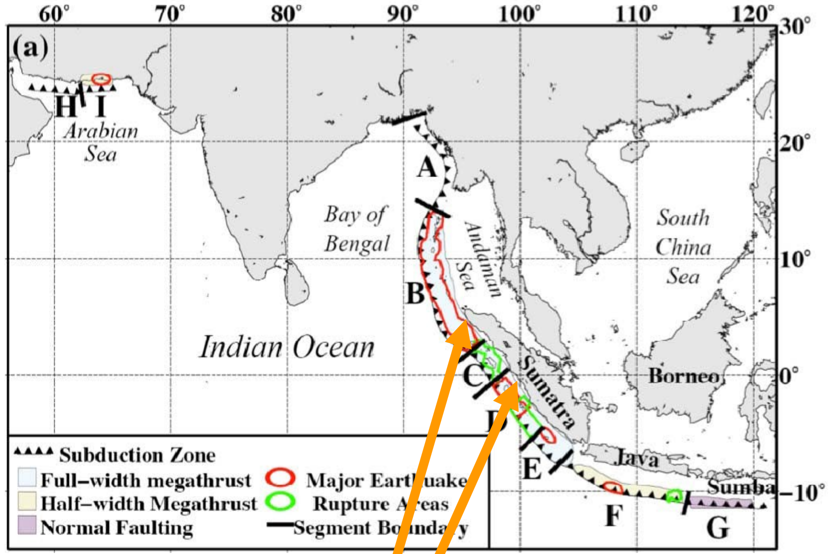
Rules of Thumb ??

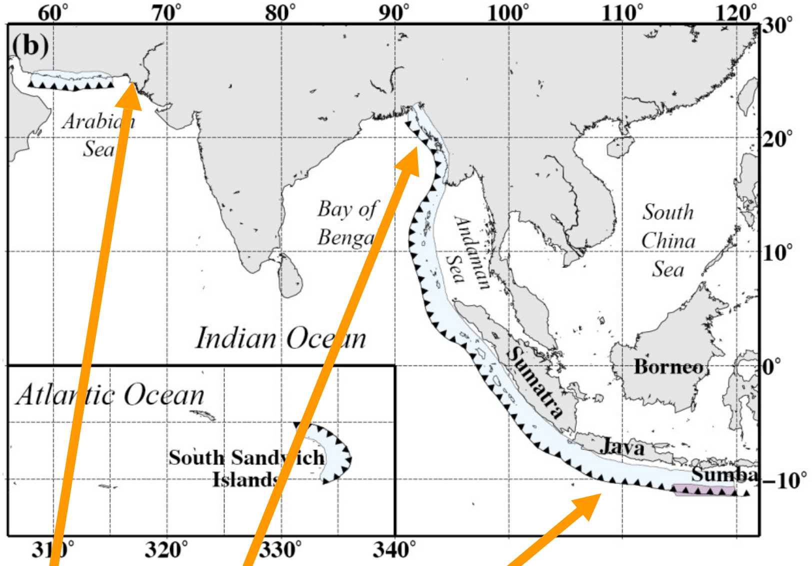
- Tsunami height at 100m water depth
  - Less than 25 cm is likely insignificant
  - 25 to 75 cm could cause significant localized run-up
  - Greater than 75 cm, a significant threat
- You may need to modify these as you learn more from inundation modelling

Re-evaluating Sources of Tsunami Risk in the Indian Ocean: Low- and High-hazard End-member Assessments

Low-hazard:
Based on historical experience

Hi-hazard: No bounds on megathrust rupture





Populations exposed to giant tsunamis by virtue of their living along coasts adjacent to subduction zones and within 3 km of coast and 10 m above sea level:

		Pakistan	0.5M
Sumatra	2M	Bangladesh	3M
		Java	1.5M

High hazard end member shows high hazard due to local tsunami along coasts with no historical precedents (Burma, Oman/Iran)

Should be followed up with detailed inundation modelling along coastlines at high risk, guided by deaggregated hazard.

Some Important Observations

- In general, there is no substitute for doing detailed inundation modelling to inform tsunami mitigation measures.
- The PTHA is an information source for deciding where and what inundation modelling is needed.
- The only way to reduce the uncertainties in the PTHA is through geologic studies of the source areas.
- Accurate inundation modelling requires high-resolution bathymetry and topography data.
- Such data are multipurpose; they can be used for flood, and storm surge modelling as well as tsunami, and this usefulness is relatively easy to sustain. As such they are sensible investment for development aid agencies.

Some Important Observations

- It is feasible to cast Probabilistic Tsunami Hazard Analysis in a same framework as PSHA
- At 475 yr return period, the height of tsunami exceedance varies around the eastern Indian Ocean from several meters to more than 20 m
- Comprehensive and uniform overview of tsunami hazard in a region
- Used in multi-hazard analysis
- Multi-regional or even global hazard analysis is feasible
- Using Green's function summation we can integrate over thousands of sources
- Disaggregation shows variation in source sensitivity between different target regions

Thank you

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