ASSESSMENT OF TSUNAMI HAZARDS FROM MANILA TRENCH TO VIETNAM USING WORST CASE SCENARIOS

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OUTLINE

- Motivation
- Source modeling
- Construction of scenarios
- Simulation
- Tsunami Hazards
- Implications
- Conclusions

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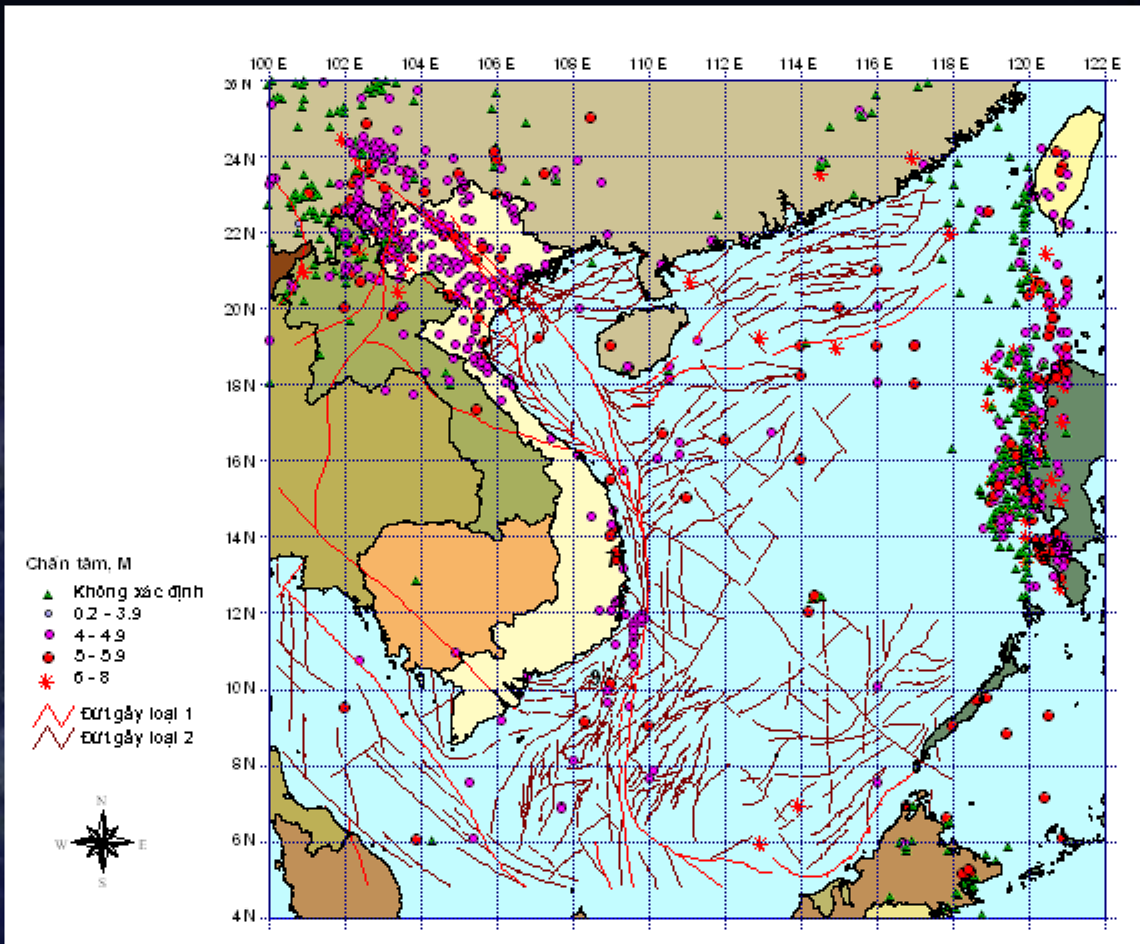
MOTIVATION



- The largest earthquakes in country: 3
  - -1 historical (in the 14th century)
  - - 2 recorded:
  - -Dien Bien 1935 (M=6.7) and Tuan Giao 1983 (M=6.8)
- Offshore volcanic Hon Tro earthquake 1923 (M=6.1)
- Offshore Vung Tau earthquake swarm 2005 (M5.5)
- No records of historical tsunamis, no official data on damage and casualties

Seismotectonic map of Vietnam and adjacent sea areas

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MOTIVATION

In less than a decade, two massive earthquakes have produced destructive tsunamis in the Indian and Pacific Oceans. The Indian Ocean tsunami of December 26, 2004 , generated by the M 9.1 Sumatra-Andaman Earthquake, was one of the deadliest natural disasters in recorded history. The Japan tsunami was generated by the M 9.0 2011 Tohoku earthquake. These two earthquakes were, respectively, the third and fourth largest ever recorded.

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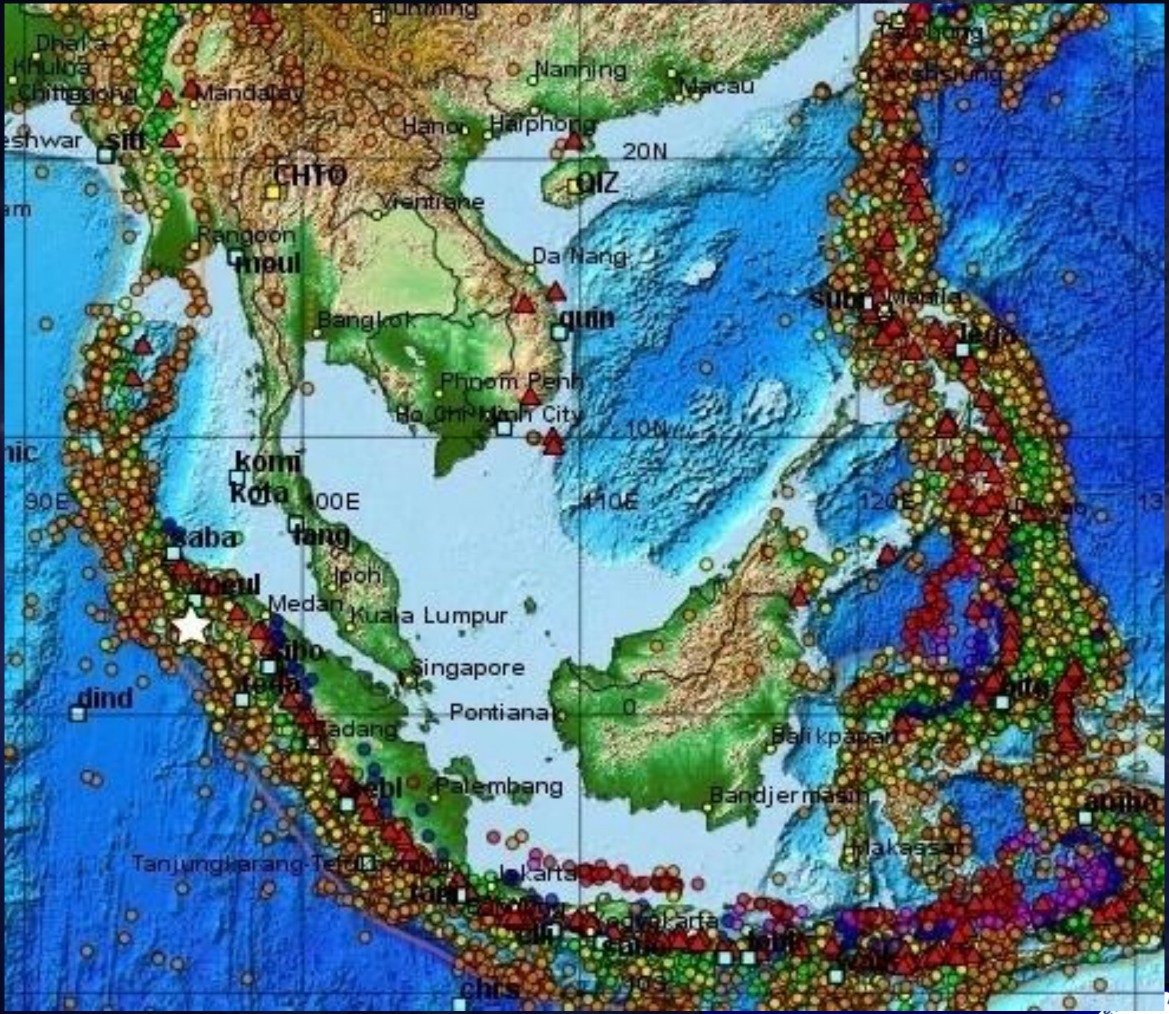
MOTIVATION

Vietnam was spared damage from these tsunamis, because of its sheltered location. These recent tragic events, however, remind us that the Vietnamese coast would be threatened by tsunamis sources in the East Vietnam Sea (South China Sea).



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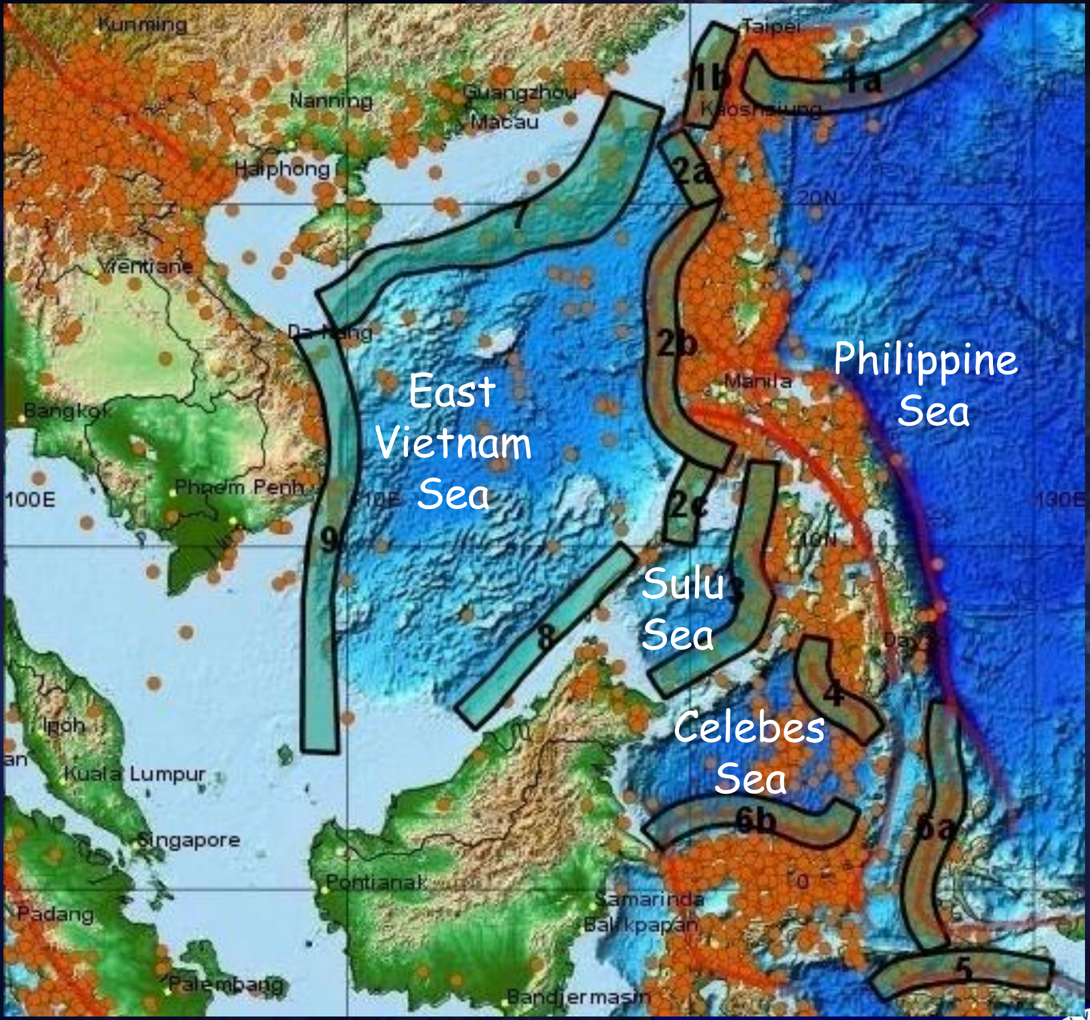
MOTIVATION

Based on analysis of tectonic feature and geodynamic characteristics of faults systems in Southeast Asia, 9 source zones capable of generating tsunamis affecting Vietnam have been identified in the South China Sea and adjacent areas.



(Nguyen et al., 2012).

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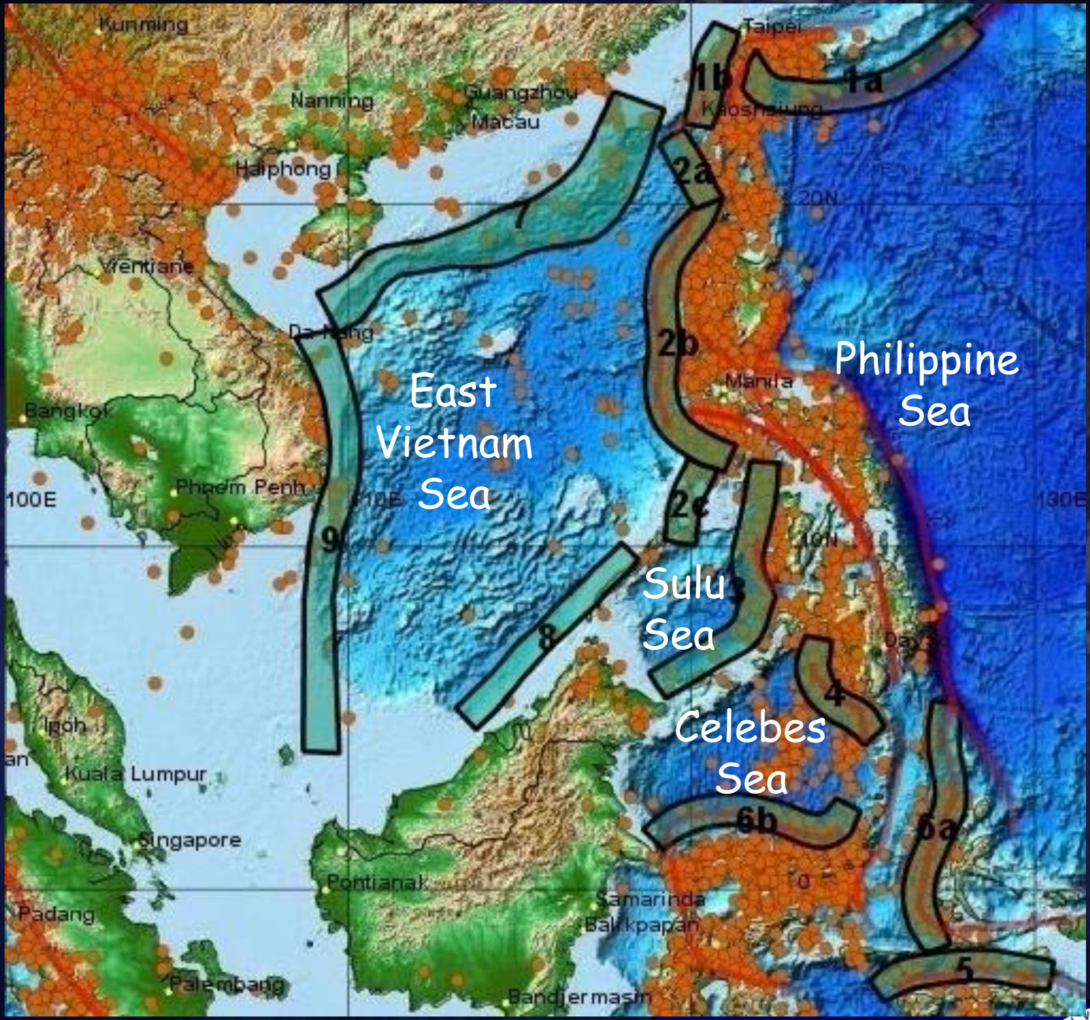
MOTIVATION

Of these, the Manila trench, west of the Philippines, would produce the most dangerous tsunamis on the Vietnamese coast.
An earthquake in the Manila Trench could conceivably reach M_w8.7; its tsunami would take approximately 2 hours to reach the Vietnamese coast



(Nguyen et al., 2012).

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MOTIVATION

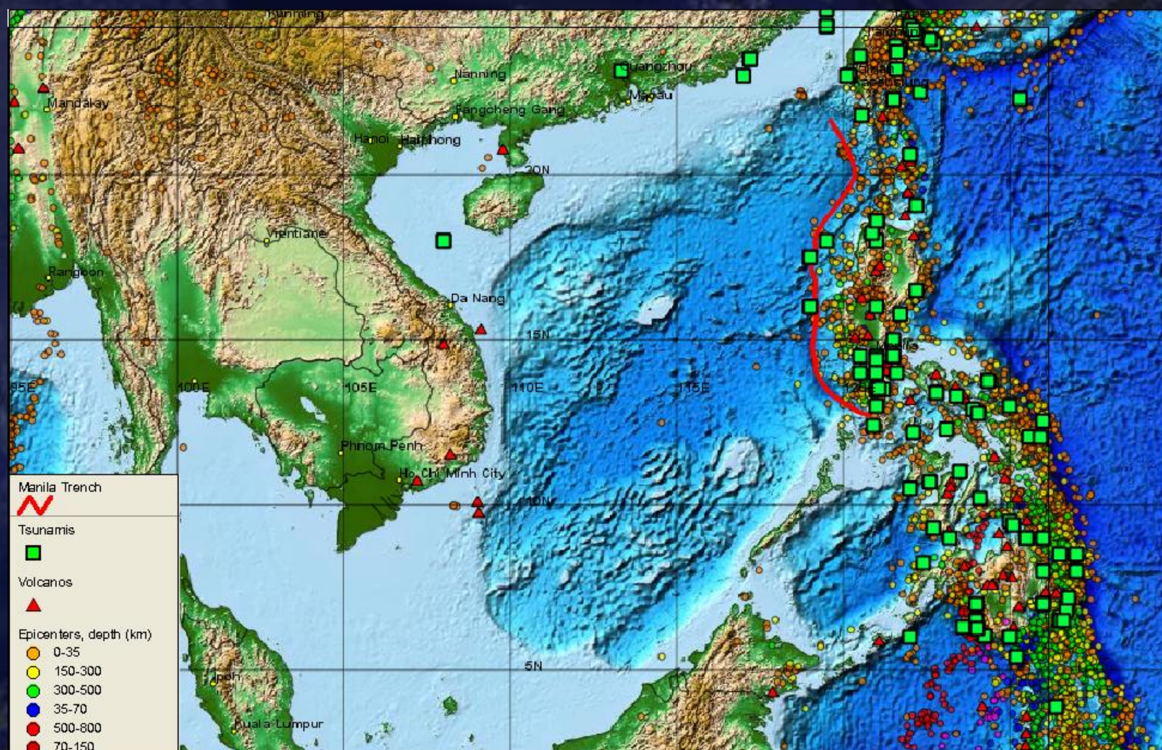
Due to the lack of historical data, tsunami warnings in Vietnam are based mainly on the pre-calculated tsunami scenarios. An attempt has been made recently to improve our understanding of tsunami hazard for Vietnam.

The COMCOT model was applied to simulate tsunami scenarios originated on the Manila Trench source and the results added to the existing database of pre-computed models for warning purposes.

The results of the worst case scenario (M_w=9.3) and some other extreme cases are used for the assessment of tsunami hazards along the Vietnamese coast.

SOURCE MODELING

A comprehensive consideration of the newly published data and most recent seismotectonic and geodynamic insights has been carried out to construct new model for the Manila Trench source.



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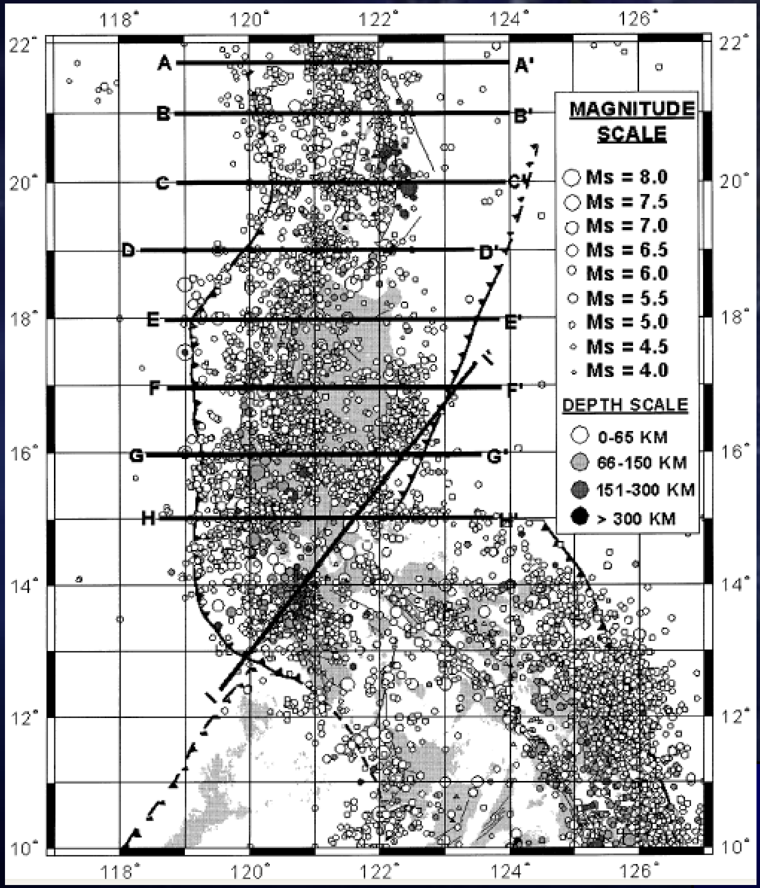
SOURCE MODELING

Bautista C. et al (2001) studied the tectonic characteristics of the Manila Trench subduction zone by developing 9 seismicity profiles across the Manila megathrust to give a 3-D imagination of the geometry and source mechanism of the subduction zone.



Bautista et al (2001)

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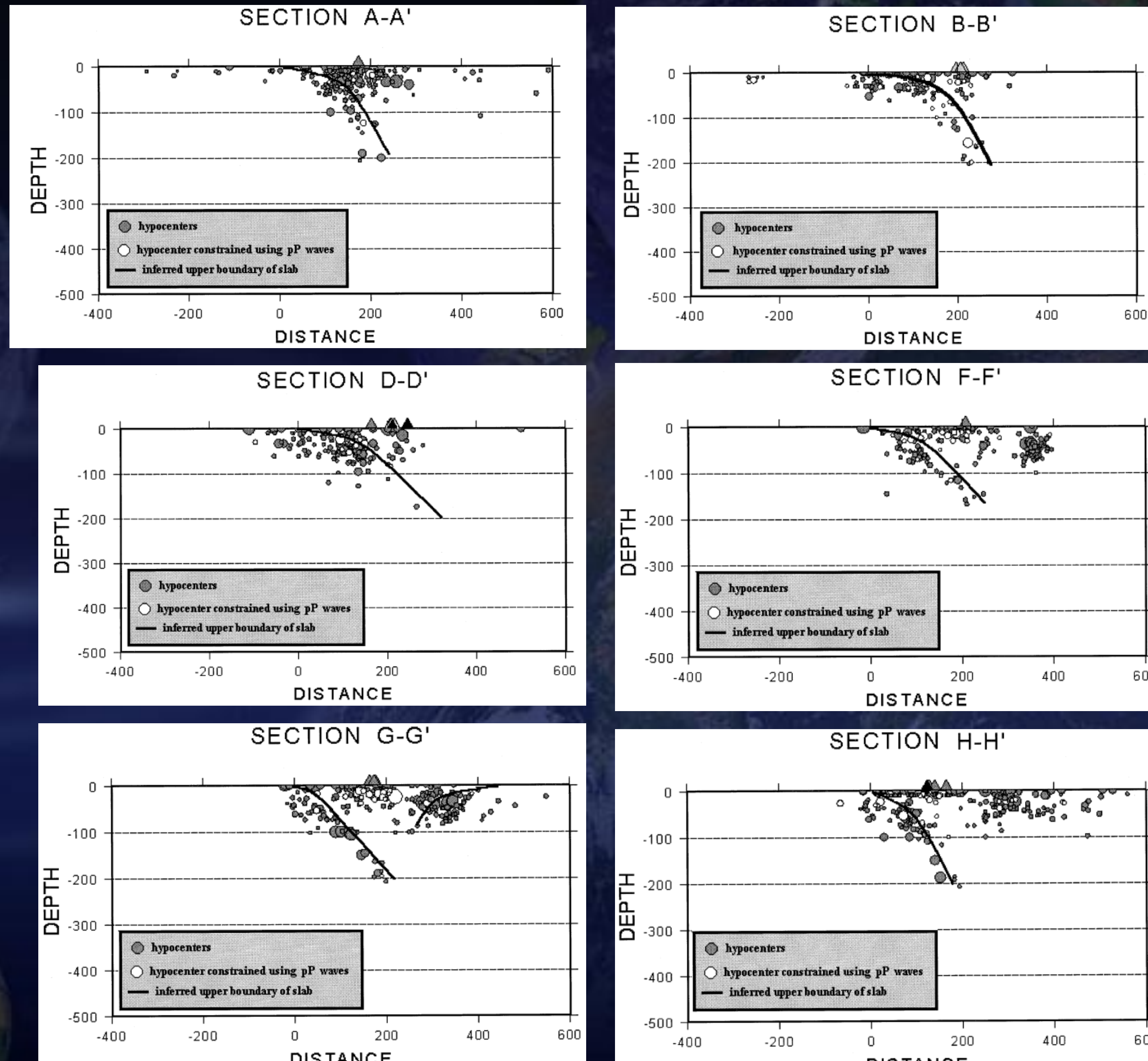
SOURCE MODELING

All cross-sections drawn along profiles with vertical seismicity and focal mechanism solutions show the tendency of slab to dip eastward to about 15^0 to 20^0 at shallow depths and go steeper as the depth increased. This evidence is surely be taken into account for determination of the dip angle during the source modeling process.

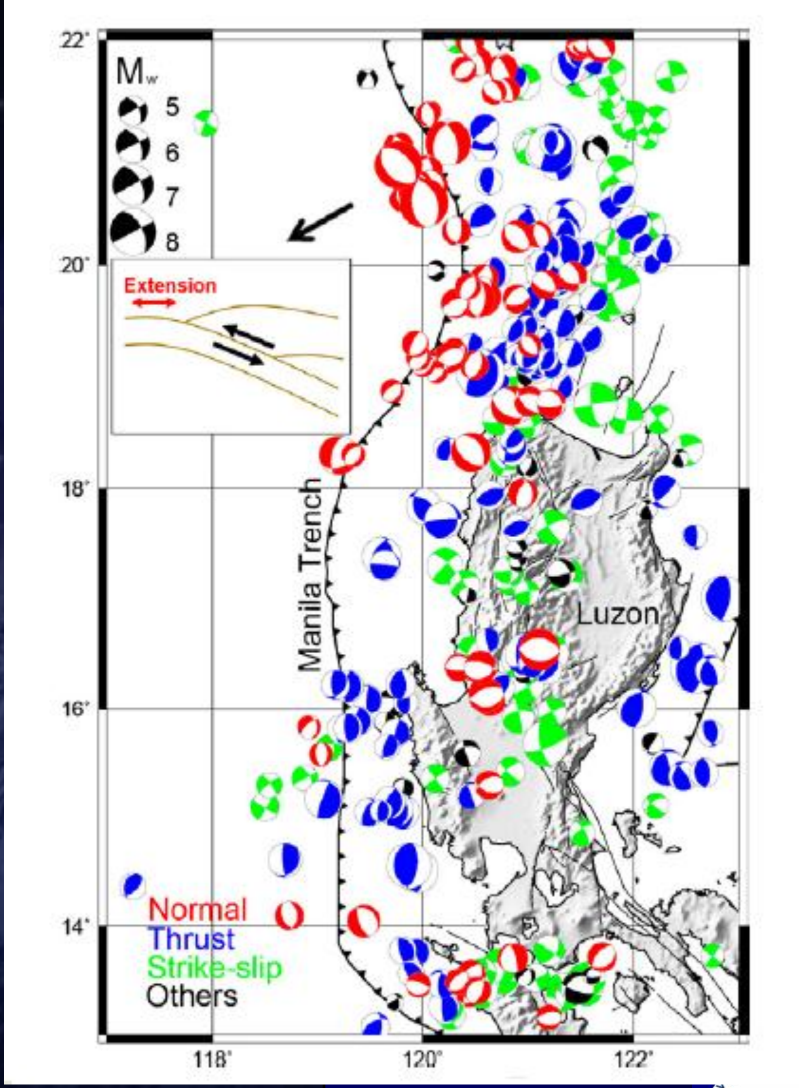


Bautista et al (2001)

SOURCE MODELING

As shown by Hsu et al (2012), normal earthquakes are concentrated in the northern part of the megathrust between 18^0N and 22^0N, while thrust events occur in the south, mostly concentrated in the segment located between 12^0N and 16^0N.

Obviously, we must consider both normal and thrust faulting as a potential source of tsunamis.



Hsu et al (2012)

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SOURCE MODELING

In this study, a new model of Manila Trench source was developed for the worst case scenario, referring to two known models proposed by Wu (2009) and Megawati (2009).

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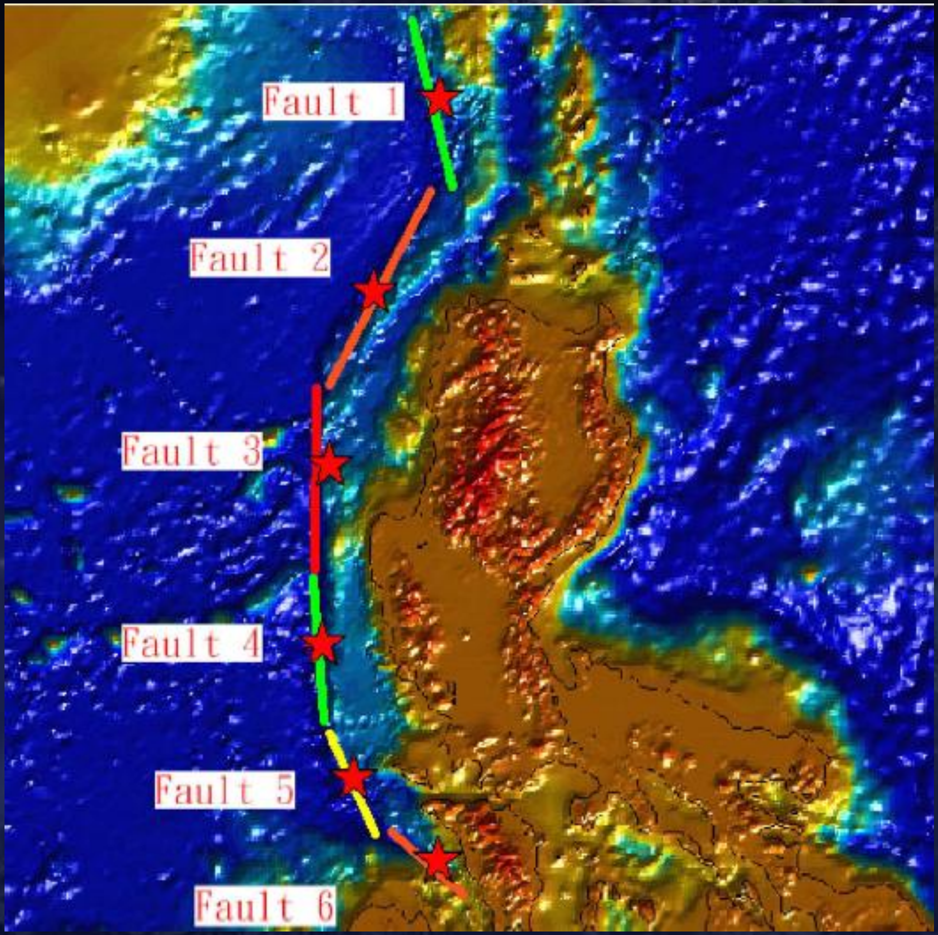
SOURCE MODELING

The source model proposed by Wu et al (2009), with its six segments, adequately imitates the megathrust. However, the use of the uniform width of 200 km for all segments is a poor representation of the actual megathrust.



Wu et al (2009)

SOURCE MODELING

Megawati et al (2009) developed a rupture model, which was obtained by interpolation over ten seismic cross sections from the studies by Bautista et al. (2001) and one cross section obtained by Wu et al. (2007). Based on GPS data, the slip values in the area of greatest relative motion were set to 40 m, and the slip is assumed to be constant approximately perpendicular to the trench axis. Then, in order to find the vertical seafloor displacement, the entire source zone was discretized into 33 rectangular elements.

The main advantage of the Megawati's model is that in this model the width of each segment is assigned corresponding with the slip value obtained by the interpolation method.

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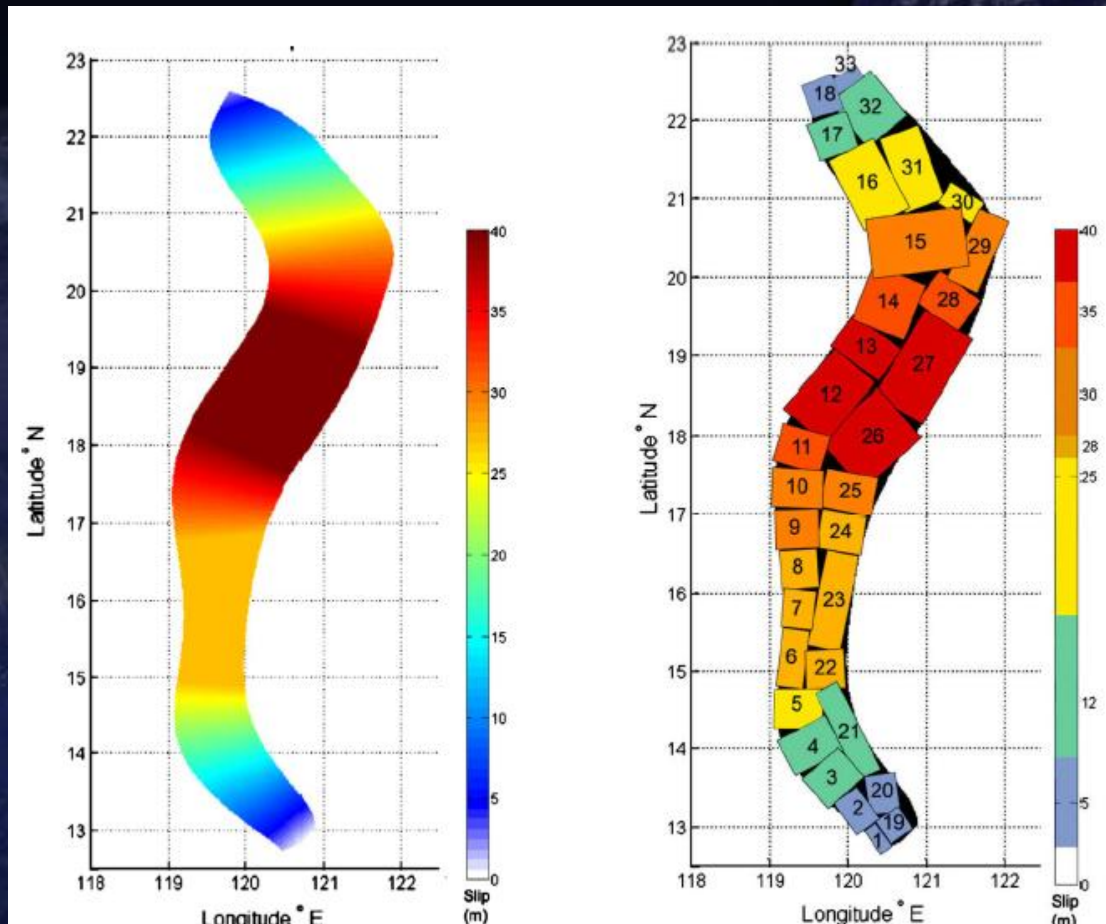
SOURCE MODELING



The slip model (left); and the discretized model of the Manila trench for computation of seafloor displacement proposed by Megawati et al (2009).

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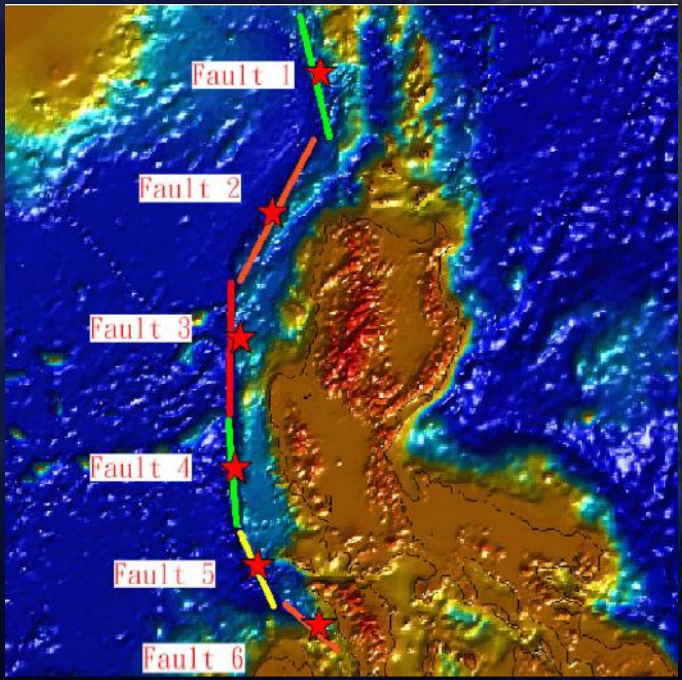
SOURCE MODELING

A worst case source model of the Manila trench was created for use in this study, incorporating all advantages of the two models described above. Geometrically, the model imitates a 6-segments shape of the Manila trench, but with the parameters modified to fit the size and shape of each segment in the map. In addition, the dislocation of each segment is assigned in accordance with the slide values defined by the Megawati's model. As in this case the source length should be long enough to sustain the M_w9.3 tsunamigenic earthquake, the slips are assumed to occur instantaneously on all six segments, and the whole Manila Trench thrust will act as one giant source.

SOURCE MODELING

Seg.	Long.	Lat.	Length (km)	Width (km)	Dislocation (m)	Depth (km)	Strike (deg.)	Dip (deg.)	Rake (deg.)
1	120.5	20.2	190	120	25	30	354	10	90
2	119.8	18.7	250	160	40	30	22	20	90
3	119.3	17.0	220	160	40	30	2	28	90
4	119.2	15.1	170	90	28	30	356	20	90
5	119.6	13.7	140	110	12	30	344	22	90
6	120.5	12.9	95	80	5	30	331	26	90



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CONSTRUCTION OF SCENARIOS

The modeling of the Manila trench source zone was a basis for the construction of tsunamigenic earthquake scenarios.

The empirical relationships of Wells and Coppersmith (1994) were used for establishing the fault parameters of tsunami sources. The procedure of defining parameters of a trench segment includes the following steps:

1. *Specify the scenario earthquake magnitude M_w (6.5 – 9.3)*
2. *Specify the scenario earthquake's epicenter.* From the epicenter and the known megathrust interface geometry, the focal depth is set to the appropriate pre-determined values (15, 30, or 55 km).

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CONSTRUCTION OF SCENARIOS

3. Determine the rupture length L from the earthquake magnitude M_w.

The L value can be calculated using the empirical relationship between fault rupture length and moment magnitude. Depending on the value of focal depth H defined in previous step, two empirical relationships for the cases of surface rupture length and subsurface rupture length can be used for determination of L (Wells and Coppersmith, 1994):

$$\log L = -2.86 + 0.63M_w \quad \text{for } H = 15 \text{ km or } H = 30 \text{ km} \quad (1)$$

$$\log L = -2.42 + 0.58\,Mw \quad \text{for } H = 55 \text{ km} \quad (2)$$

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CONSTRUCTION OF SCENARIOS

4. Determine the rupture area A and the rupture width W of the fault source from earthquake magnitude M_w.

The rupture area of the fault source is defined as a function of moment magnitude for the case of reverse fault (Wells and Coppersmith, 1994):

$$\mathrm{Log}A = -3.99 + 0.98\,M_w \qquad (3)$$

With assumption of the rectangular rupture zone with area A and length L, the rupture width W can be found.

5. Determine the displacement D from the earthquake magnitude M_w.

The all-slip-type empirical equation was used for determination of average displacement D_{av} (Wells and Coppersmith, 1994):

$$\mathrm{Log}\,D_{av} = -4.80 + 0.69\,M_w \qquad (4)$$

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CONSTRUCTION OF SCENARIOS

6. Check the fitness of the source parameters:

As the fault parameters were obtained from the empirical relationships with different reliabilities, the Hanks and Kanamori formula (1979) was used for verification of the fitness and adjustment of the fault parameters:

$$M_w = 2/3\log_{10}M_0 - 10.7 \qquad (5)$$

where $M_0 = \mu DLW$ is the seismic moment and $\mu = 3 \times 10^{10}$ N/M is the shear modulus.

SIMULATION

The well validated COMCOT (Cornell Multi-grid Coupled Tsunami Model), is chosen to perform the simulation.

The COMCOT model is capable of solving both linear and nonlinear shallow water equations in the spherical and Cartesian coordinate systems. The nested grid system can provide tsunami simulations in both deep-water and near-shore coastal regions. The COMCOT model also provides the moving boundary algorithm to simulate the tsunami inundation (Philip L. –F. Liu et al, 1998).

The linear SWE:

$$\frac{\partial \eta}{\partial t} + \frac{1}{R\cos\varphi}\left\{\frac{\partial P}{\partial \psi} + \frac{\partial}{\partial \varphi}(\cos\varphi Q)\right\} = -\frac{\partial h}{\partial t} \qquad (6)$$

$$\frac{\partial P}{\partial t} + \frac{gh}{R\cos\varphi}\frac{\partial \eta}{\partial \psi} - fQ = 0 \qquad (7)$$

$$\frac{\partial Q}{\partial t} + \frac{gh}{R}\frac{\partial \eta}{\partial \varphi} + fP = 0 \qquad (8)$$

The nonlinear SWE:

$$\frac{\partial \eta}{\partial t} + \frac{1}{R\cos\varphi}\left\{\frac{\partial P}{\partial \psi} + \frac{\partial P}{\partial \varphi}(\cos\varphi Q)\right\} = -\frac{\partial h}{\partial t} \qquad (10)$$

$$\frac{\partial P}{\partial t} + \frac{1}{R\cos\varphi}\frac{\partial}{\partial \psi}\left\{\frac{P^2}{H}\right\} + \frac{1}{R}\frac{\partial}{\partial \varphi}\left\{\frac{PQ}{H}\right\} + \frac{gH}{R\cos\varphi}\frac{\partial \eta}{\partial \psi} - fQ + F_x = 0 \qquad (11)$$

$$\frac{\partial Q}{\partial t} + \frac{1}{R\cos\varphi}\frac{\partial}{\partial \psi}\left\{\frac{PQ}{H}\right\} + \frac{1}{R}\frac{\partial}{\partial \varphi}\left\{\frac{Q^2}{H}\right\} + \frac{gH}{R}\frac{\partial \eta}{\partial \varphi} - fP + F_y = 0 \qquad (12)$$

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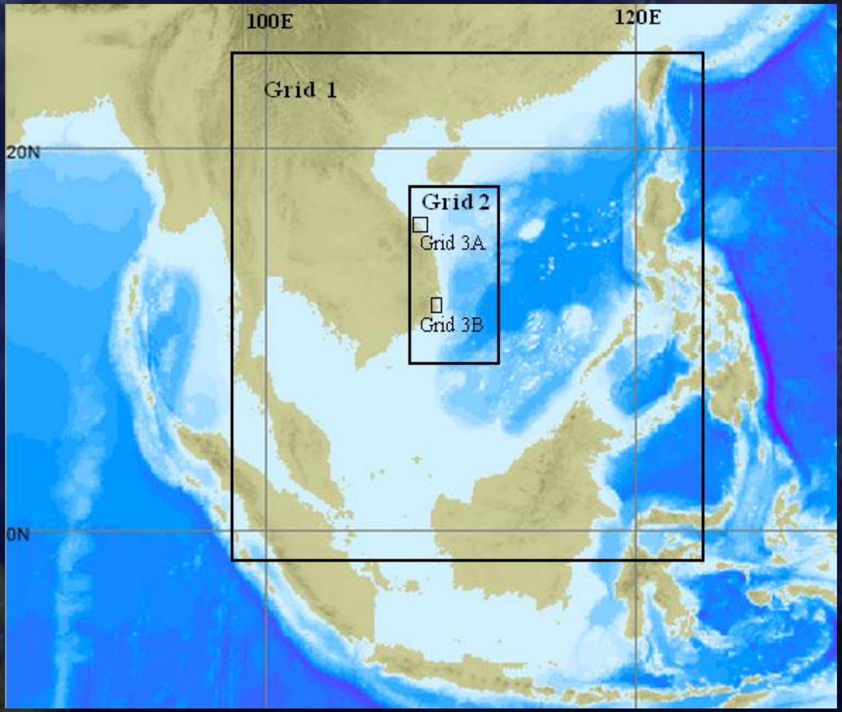
SIMULATION

Three-layer nested grids are adopted and referred as Grids 1, 2, and 3.

The grid information of three grid layers.

	Grid 1	Grid 2	Grid 3A	Grid 3B
Coordinate	Spherical	Spherical	Spherical	Spherical
Governing equations	Linear SWE	Linear SWE	Nonlinear SWE	Nonlinear SWE
Grid size	1′	0.5′	0.03125′	0.03125′
Use of bottom friction	No	Yes	Yes	Yes
Manning's roughness coefficient	No	0.025	0.025	0.025
Cell number in *X* direction	1621	478	1056	480
Cell number in *Y* direction	1621	1078	576	448



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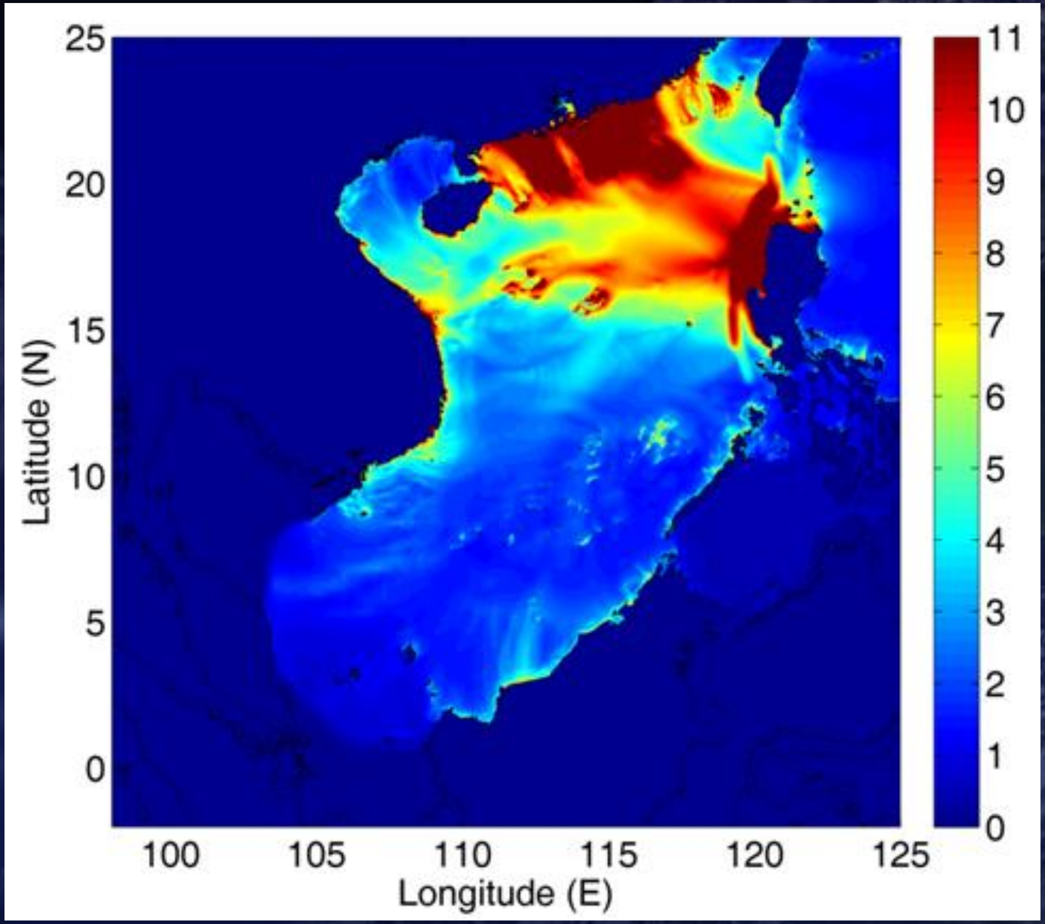
TSUNAMI HAZARDS



Maximum free-surface elevation on Grid 1 (The East Vietnam Sea) according to the E3 Worst case scenario, M_w=9.3).

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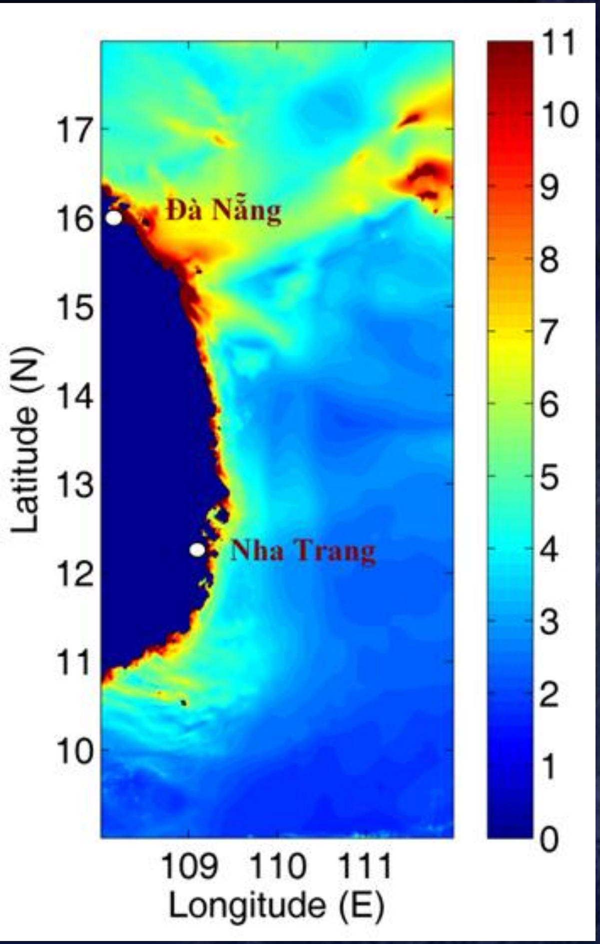
TSUNAMI HAZARDS



Maximum free-surface elevation on Grid 2 (Central Vietnam coast) according to the E3 Worst case scenario, M_w=9.3).

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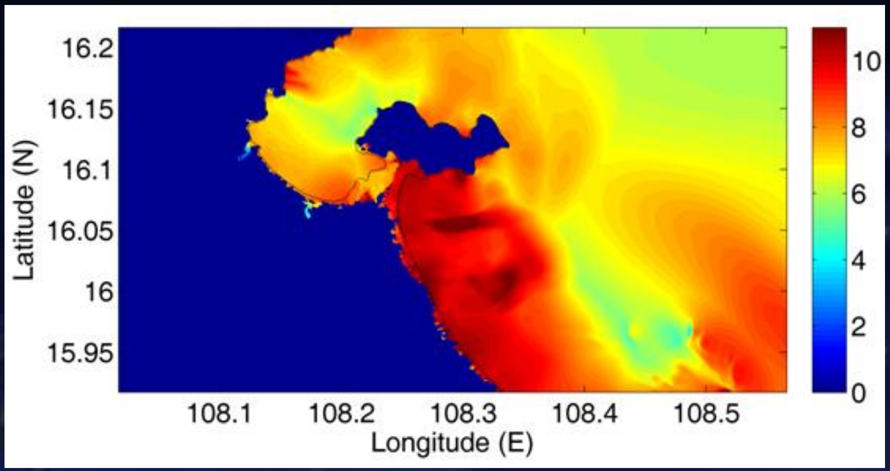
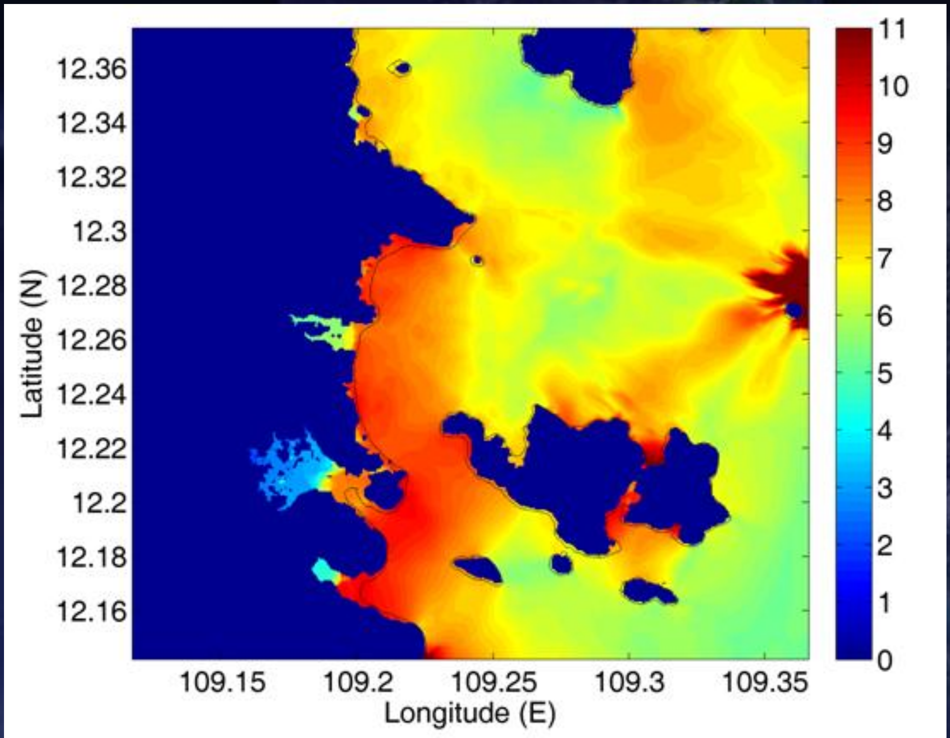
TSUNAMI HAZARDS





Maximum free-surface elevation on Grid 3: Wave heights maps calculated for Da Nang city (left) and Nha Trang city (right) according to the E3 Worst case scenario, M_w=9.3).

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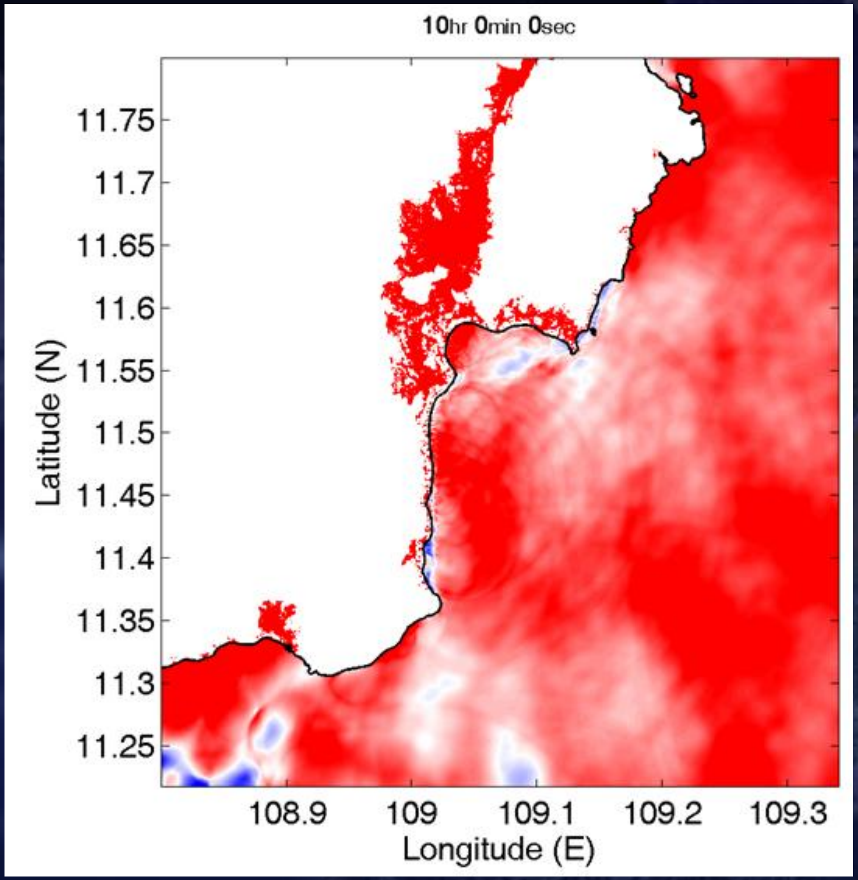
TSUNAMI HAZARDS



Results after 10 h of running the simulation, the E2 scenario, Ninh Thuan coast

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TSUNAMI HAZARDS

To study the characteristics of the tsunamis, several virtual wave gauges are constructed along the Vietnamese coast.

Sea level station	Long	Lat
Hòn Dáu_Hải Phòng	106.818300	20.665300
Giao Thủy_Nam Định	106.559000	20.158600
Cửa Lò – Nghệ An	105.756000	18.824500
Đồng Hới – Quảng Bình	106.668000	17.479900
Đà Nẵng	108.250000	16.075000
Hội An	108.432000	15.877900
Núi Thành – Quảng Nam	108.800000	15.488600
Nghĩa An – Quảng Ngãi	108.920000	15.118900
Quy Nhơn 2	109.303000	13.774900
Tuy Hòa	109.379000	13.083200
Nha Trang	109.198500	12.239400
Ninh Thuận	109.027000	11.410000
Vũng Tầu	107.083800	10.319700
Cà Mau	104.850000	8.545000

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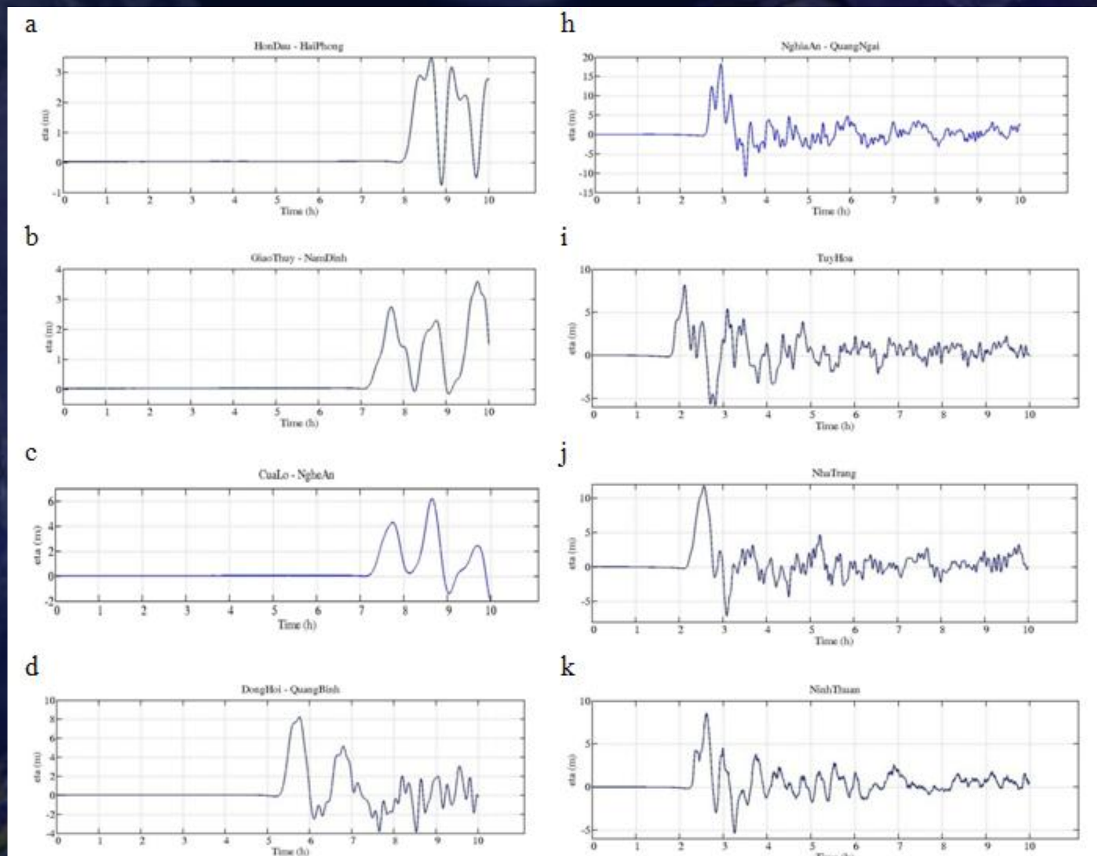
TSUNAMI HAZARDS

The time-history of free-surface elevations at the virtual wave gauges locations are calculated from the E3 worst case scenario. Time zero value denotes the moment when tsunami occurs.



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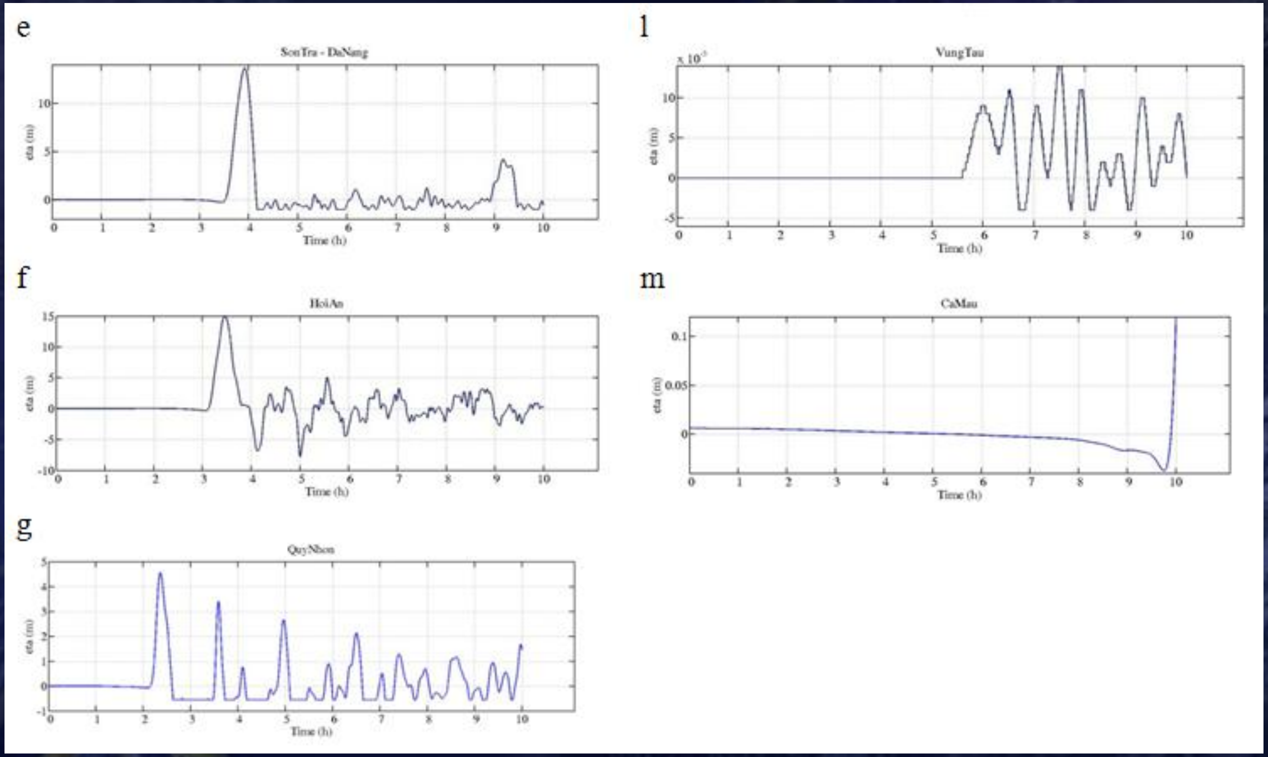

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TSUNAMI HAZARDS

Location	Longitude	Latitude	Max wave (m)	Travel time (h)
Hon Dau - Hai Phong	106.8183	20.6653	3.35	8:38
Giao Thuy - Nam Dinh	106.5590	20.1586	3.31(*)	9:44 (*)
Cua Lo – Nghe An	105.7560	18.8245	6.20 (*)	8:39 (*)
Dong Hoi – Quang Binh	106.6680	17.4799	8.29	5:45
Son Tra - Da Nang	108.2500	16.0750	10.24	3:26
Hoi An	108.4320	15.8779	12.25	3:24
Nui Thanh – Quang Nam	108.8000	15.4886	10.86	2:57
Nghia An – Quang Ngai	108.9200	15.1189	18.27(*)	2:57 (*)
Quy Nhon	109.3030	13.7749	7.21	2:32
Tuy Hoa	109.3790	13.0832	8.19	2:06
Nha Trang	109.1985	12.2394	8.84	2:28
Ninh Thuan	109.0270	11.4100	8.80	2:36
Vung Tau	107.0838	10.3197	4.83	7:25
Ca Mau	104.8500	8.54500	0.12	10:00

Locations and tsunami hazard parameters at the virtual gauge stations (E3 WC scenario). Only maximum wave heights are listed in the table, asterisks indicate the cases where the maximum wave heights do not correspond to the first wave peak.

Nguyen et al (2014)

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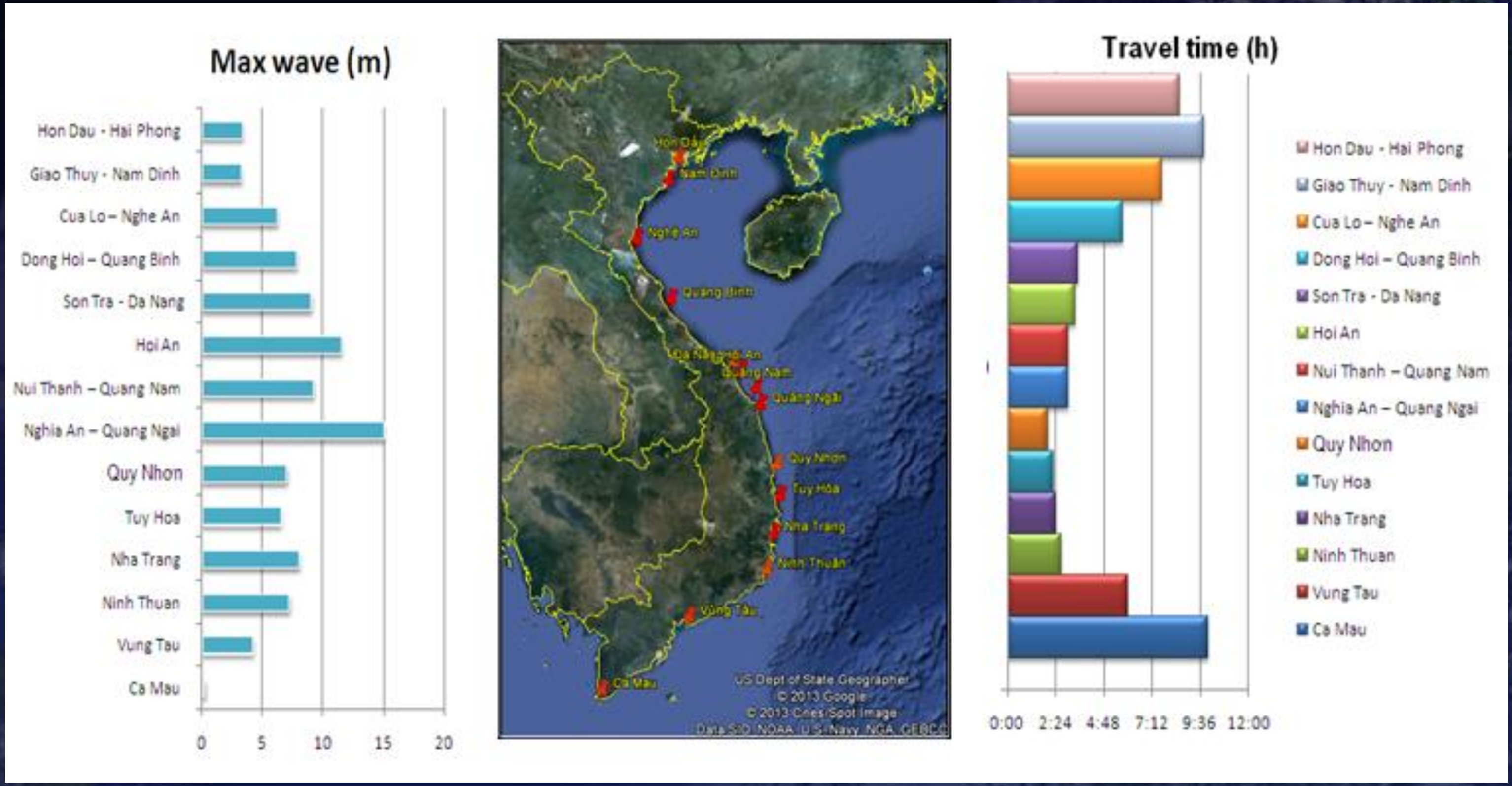
TSUNAMI HAZARDS



Map showing locations of the virtual gauges stations along the Vietnamese coast (middle) and graphs showing maximum wave height (left) and their travel times to stations (right) according to the E3 Worst case scenario, M_w=9.3.

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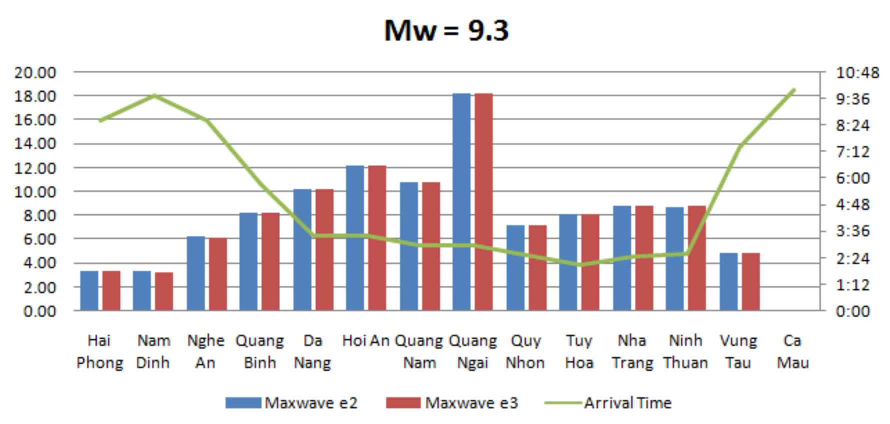
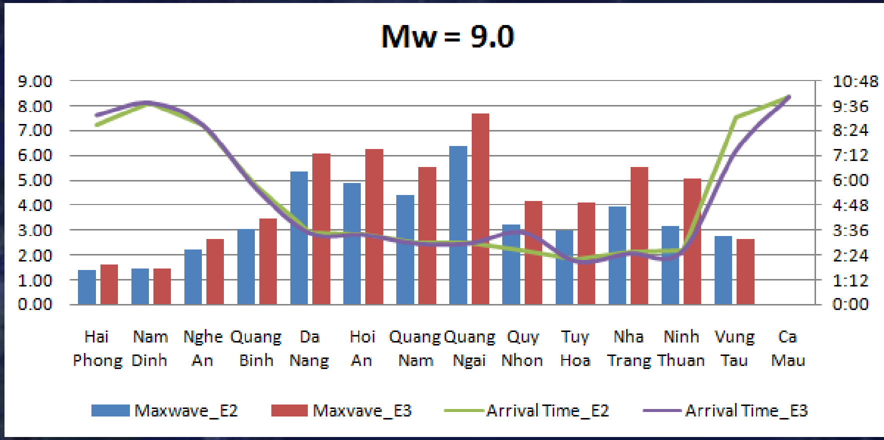
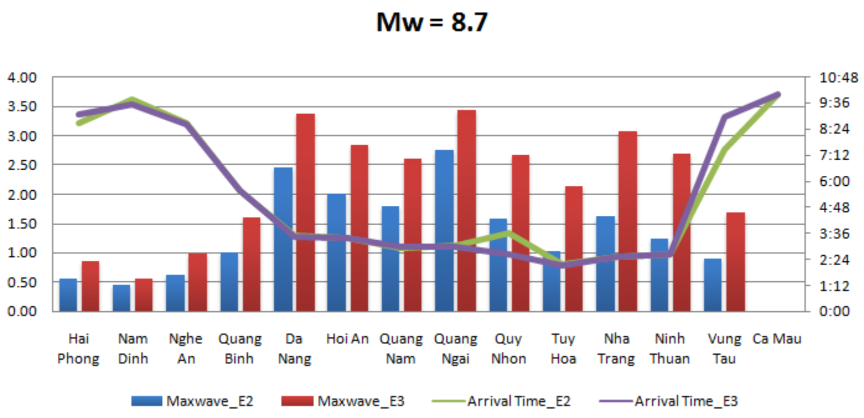
TSUNAMI HAZARDS







Investigation of the variation in calculated hazards as a function of input parameters

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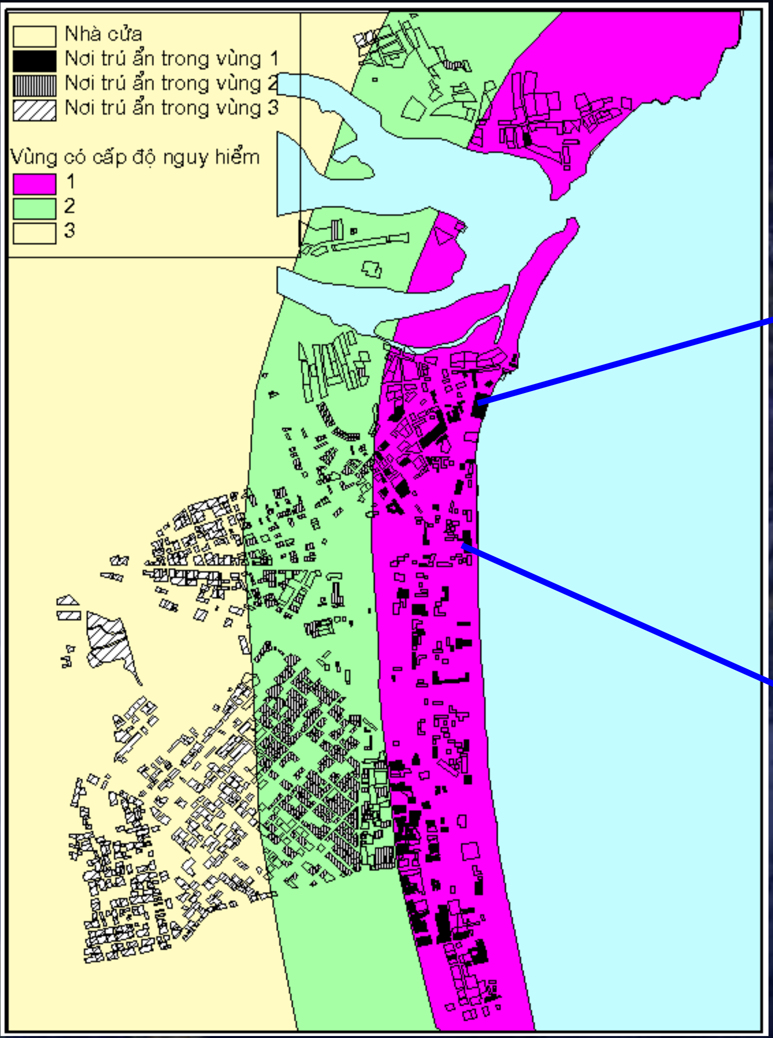
IMPLICATIONS

Tsunami shelters map for Nha Trang city: vertical evacuation



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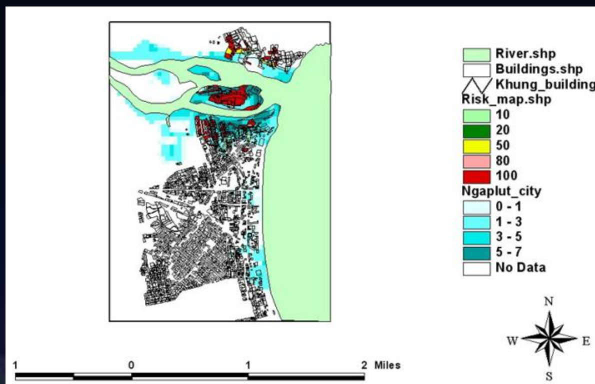
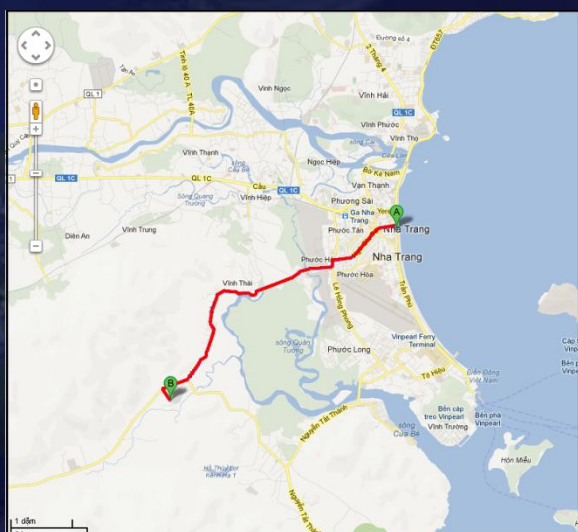
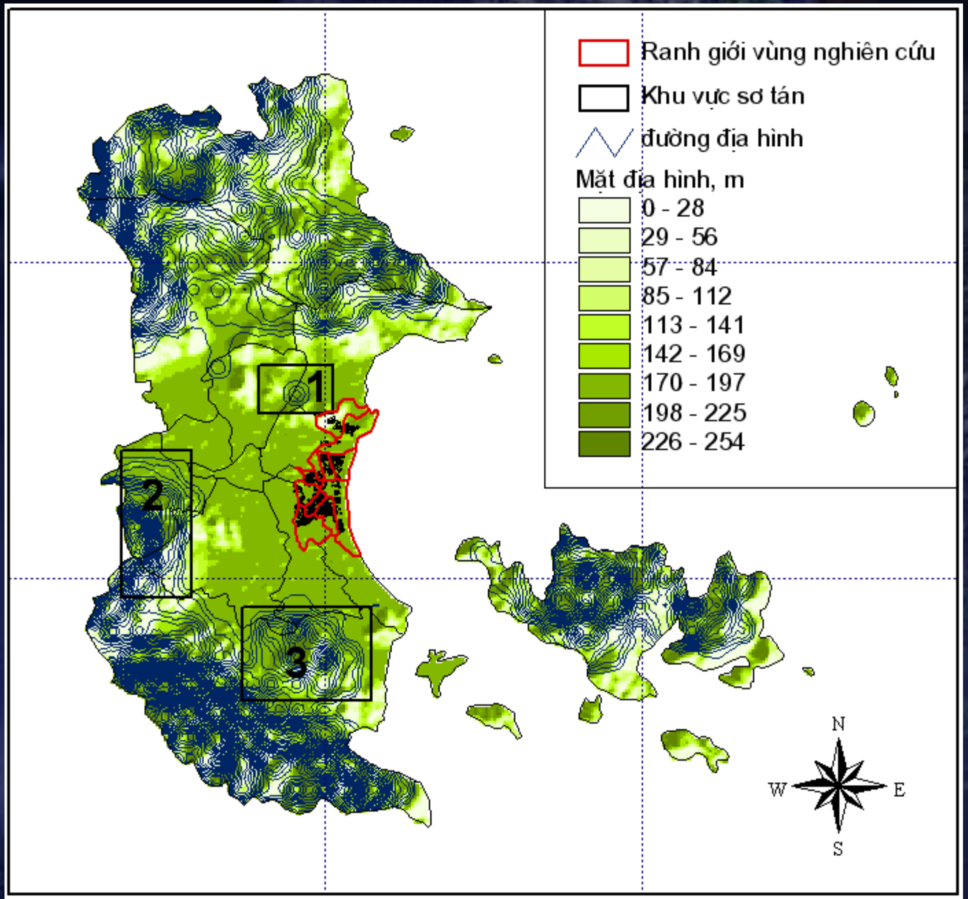
IMPLICATIONS



Tsunami risk map with inundated areas



Evacuation scenarios



Map of tsunami evacuation zones: horizontal evacuation

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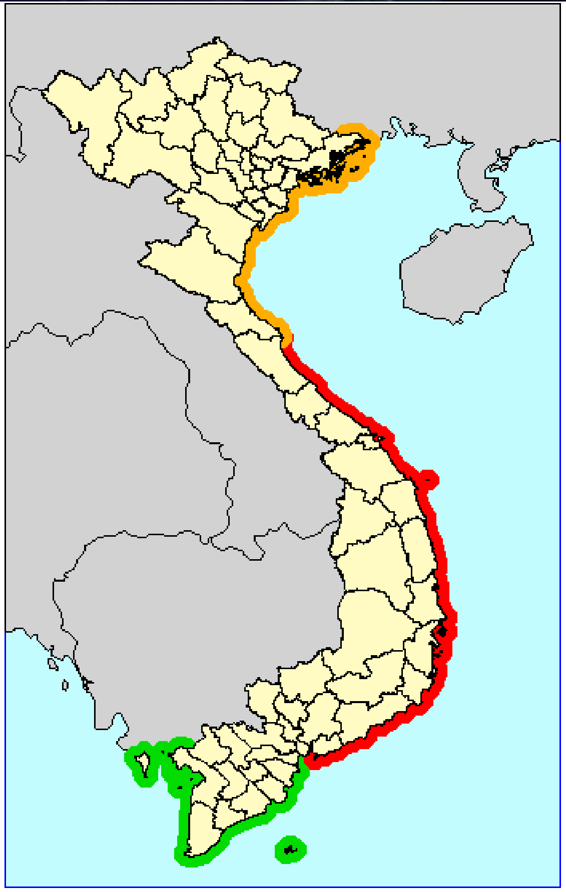
CONCLUSIONS

The simulation results show that the Vietnamese coast can be divided into three parts with different levels of tsunami hazard.



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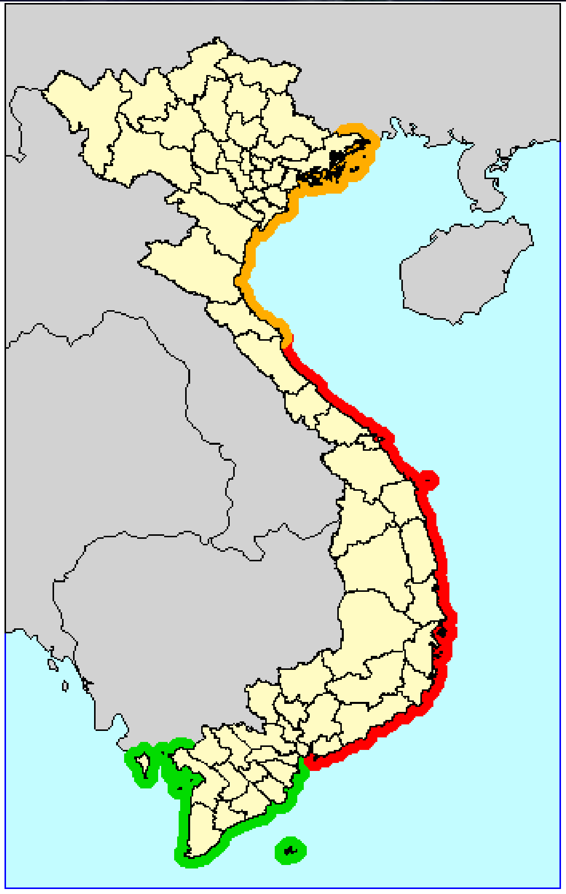
CONCLUSIONS

a) The southern coastal zone of Vietnam has lowest tsunami hazards level.

b) The northern coastal zone of Vietnam has medium tsunami hazards level.

c) Highest tsunami hazards is concentrated along the coasts of Central and northern Central Vietnam, from Quang Binh to Ba Ria – Vung Tau provinces. Maximum wave height is 18 m, observed at Quang Ngai coast. In terms of the tsunami travel time, the most vulnerable cities are Tuy Hoa (2:06 h), Nha Trang (2:28 h), Quy Nhon (2:32 h), and Ninh Thuan (2:35 h).



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CONCLUSIONS

While a very large earthquake in the Manila Trench seems improbable, the lesson from recent giant earthquakes is that every subduction zone should be regarded as "locked, loaded, and dangerous" (McCaffrey, 2008). Since the consequences are so dire, it is important to consider such extreme events.

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ASSESSMENT OF TSUNAMI HAZARDS FROM MANILA TRENCH TO VIETNAM USING WORST CASE SCENARIOS

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THANK YOU !