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Center of Excellence for Exascale in Solid Earth

Probabilistic Tsunami Hazard Analysis: Pushing the Limits with High Performance Computing

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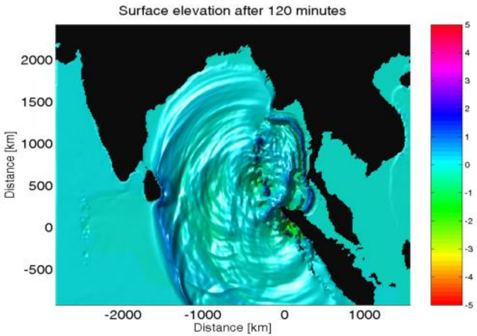
The Tsunami Hazard ...

Indian Ocean Tsunami - 2004

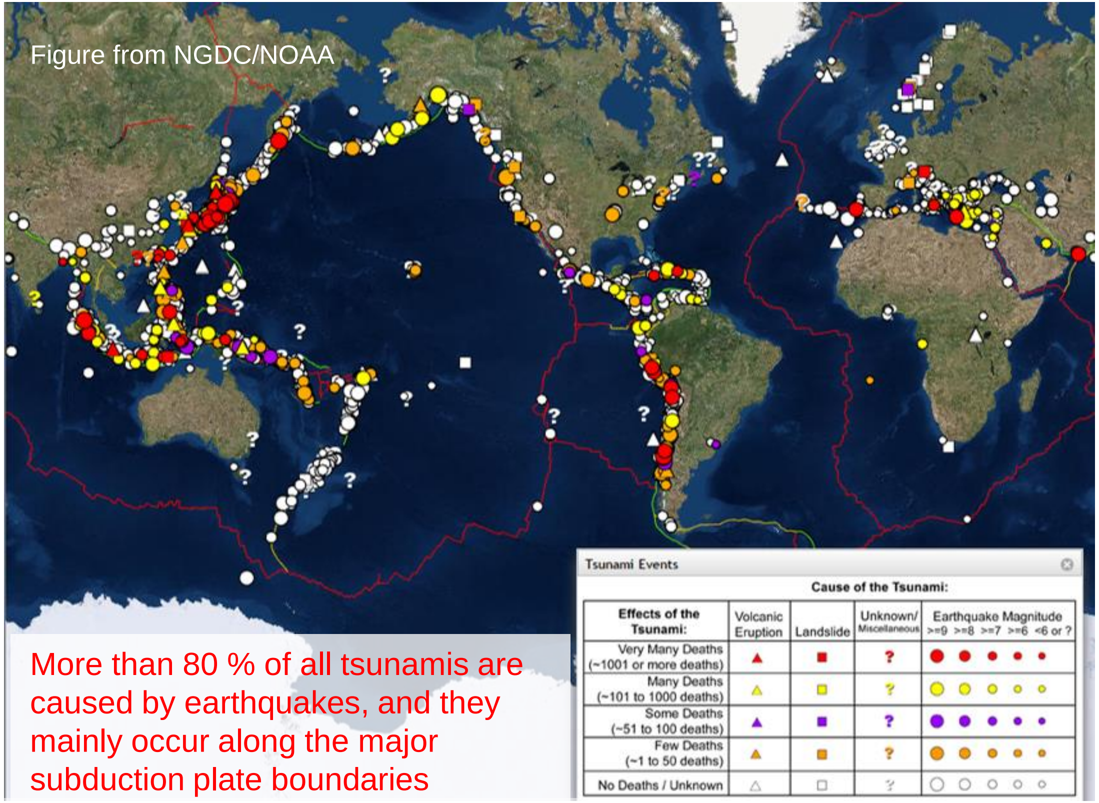
- Around 230.000 fatalities
- Up to 51 m run-up (near Banda Aceh)
- Rupture length ~1200 km, slip 20-25 m



Tohoku earthquake and tsunami - 2011

- Around 20.000 fatalities
- 130.000 buildings totally collapsed
- Up to 40 m run-up
- NE Japan displaced up to 2.4 m eastward

Causes of Tsunamis …



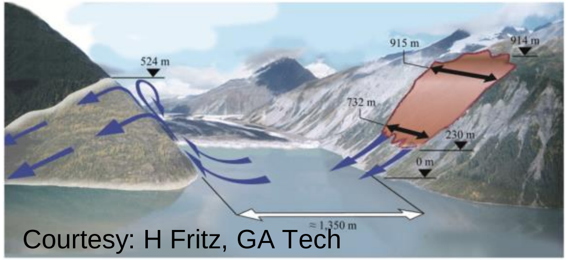
Effects of the Tsunami:	Volcanic Eruption	Landslide	Unknown/ Miscellaneous	Earthquake Magnitude >=9 >=8 >=7 >=6 <6 or ?
Very Many Deaths (~1001 or more deaths)	▲	■	?	● ● ● ● ●
Many Deaths (~101 to 1000 deaths)	▲	■	?	● ● ● ● ●
Some Deaths (~51 to 100 deaths)	▲	■	?	● ● ● ● ●
Few Deaths (~1 to 50 deaths)	▲	■	?	● ● ● ● ●
No Deaths / Unknown	△	□	?	○ ○ ○ ○ ○

More than 80 % of all tsunamis are caused by earthquakes, and they mainly occur along the major subduction plate boundaries

Significant hazard can be associated with smaller magnitude earthquakes.

Lituya Bay 1958

> 500 m run-up



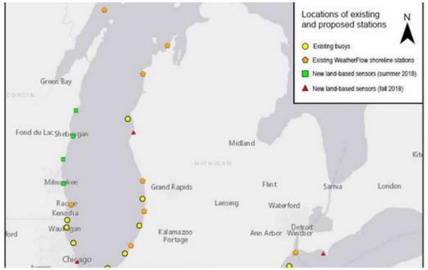
Courtesy: H Fritz, GA Tech

AUGUST 3, 2018

Pilot project to warn of potentially dangerous 'meteotsunami' waves in Great Lakes

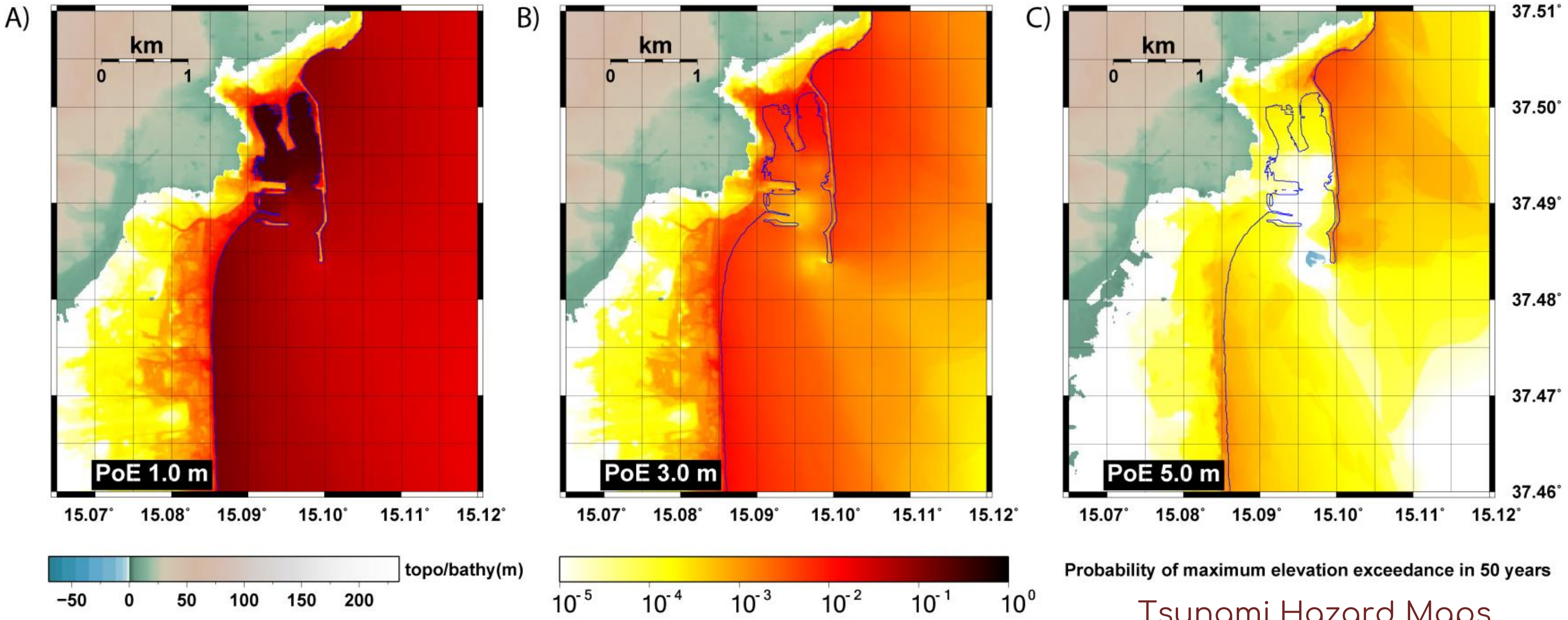
phys.org

by University of Michigan



Experimental Great Lakes meteotsunami in Michigan. Credit: LimnoTech

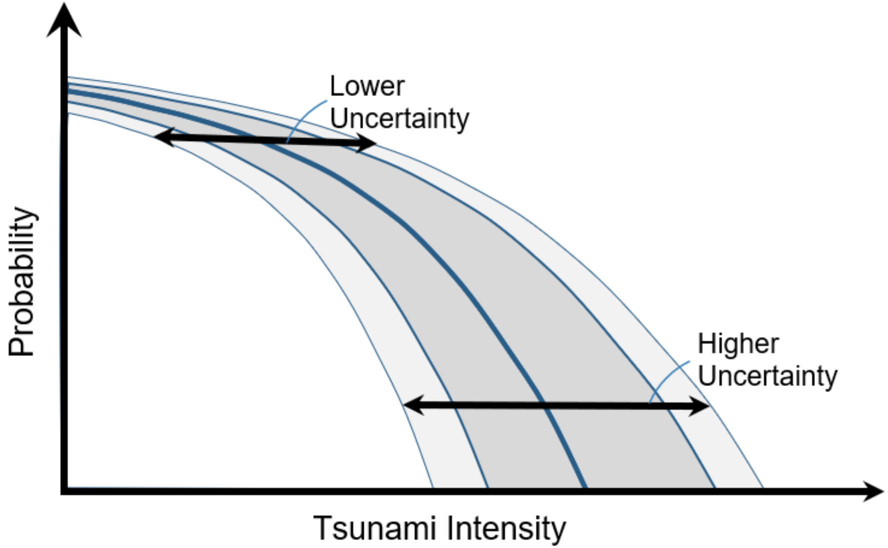
Probabilistic Tsunami Hazard Analysis



Tsunami Hazard Maps

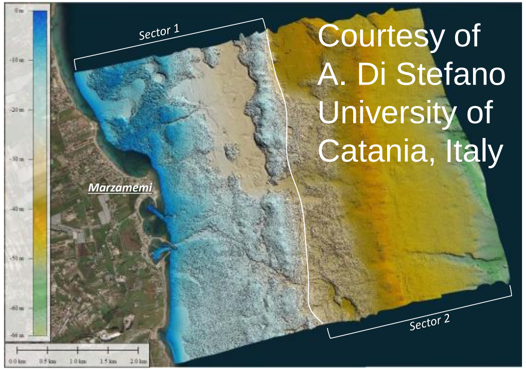
PTHA estimates the probability of exceeding a given tsunami inundation metric at a given location in a given time interval.

Probabilistic Tsunami Hazard Analysis



Examples of Applications and Stakeholders

- Insurance Premiums
- Emergency Planning (Evacuation Routes)
- Coastal Engineering (Planning Constraints)
- Civil Protection (Hazard Zonation for Emergency Planning)



Courtesy of A. Di Stefano University of Catania, Italy

PTHA estimates the probability of exceeding a given tsunami inundation metric at a given location in a given time interval.

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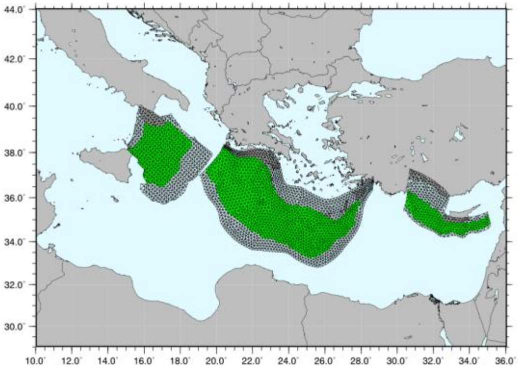
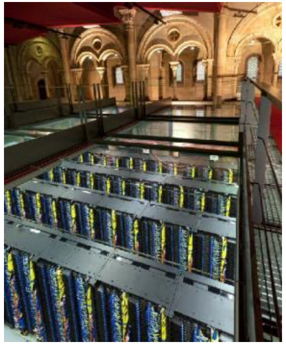
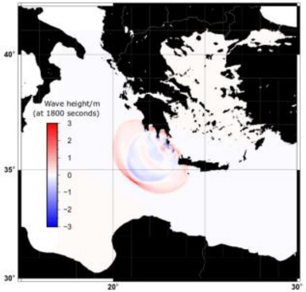
Probabilistic Tsunami Hazard Analysis

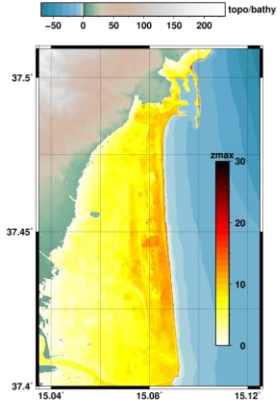


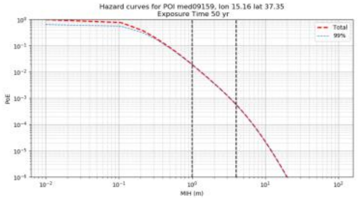
- Tsunamigenic earthquakes
- Vast number of «scenarios»
- Subduction earthquakes with variable slip distributions on well-understood fault geometries
- «Background seismicity» – crustal earthquakes with more uncertain properties.





- Tsunami simulation
- 1000s of parallel calculations (HPC required!)





- Hazard calculation
- Visualization for stakeholders

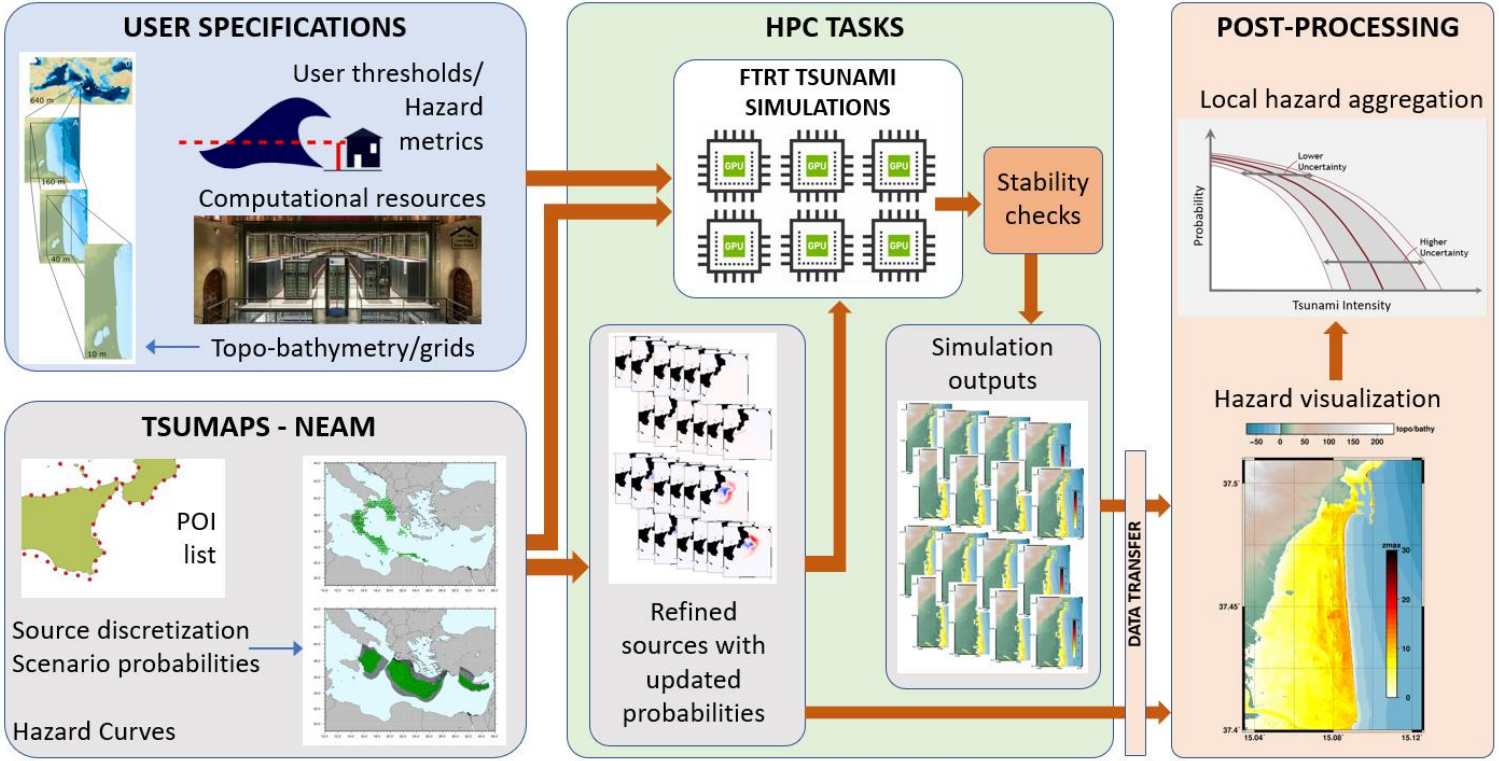
Probabilistic Tsunami Hazard Analysis

The contribution of the ChEESE CoE – Why do we need HPC now?

- Past assessment (TSUMAPS) – inundation estimated from offshore wave height – huge uncertainty
- Coarse hazard estimates – every 20 km.

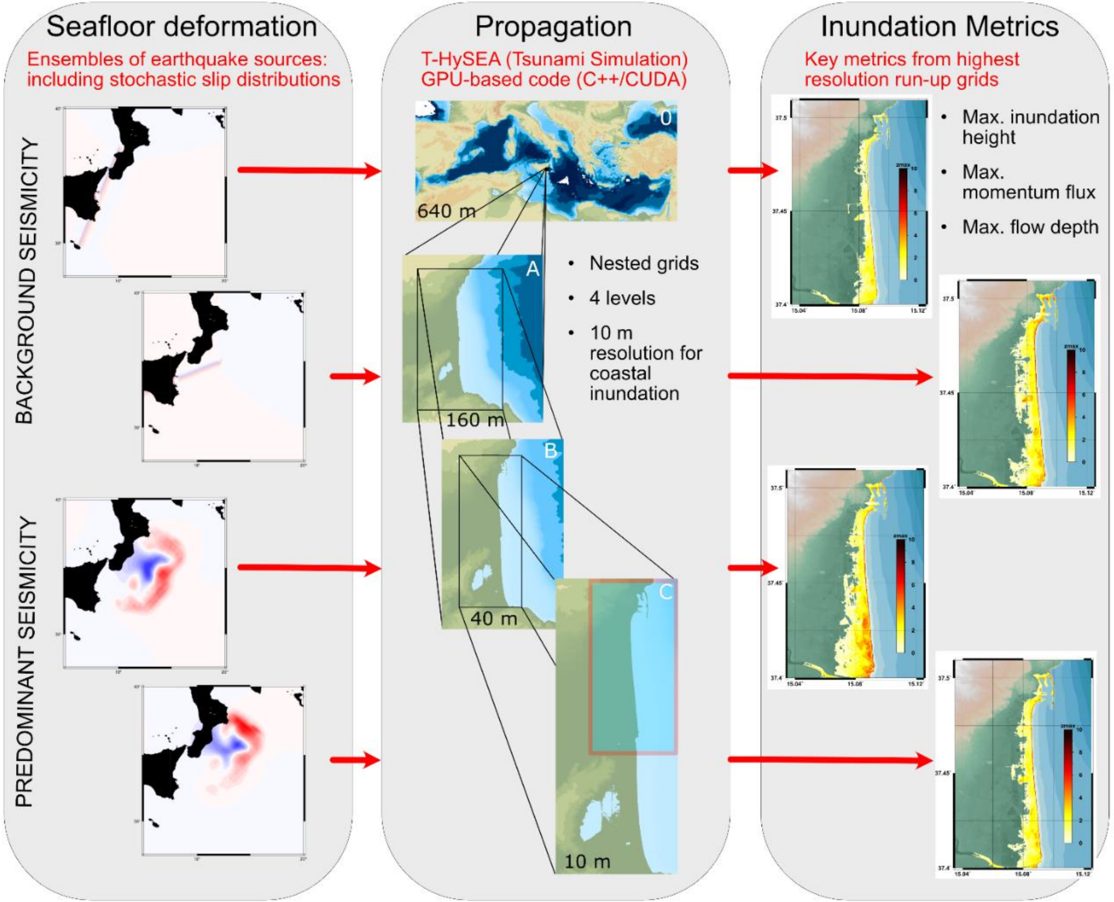
- ChEESE – high resolution inundation calculations.
- Vastly more expensive computationally.
- Much more accurate, reduce constrained areas.

Probabilistic Tsunami Hazard Analysis



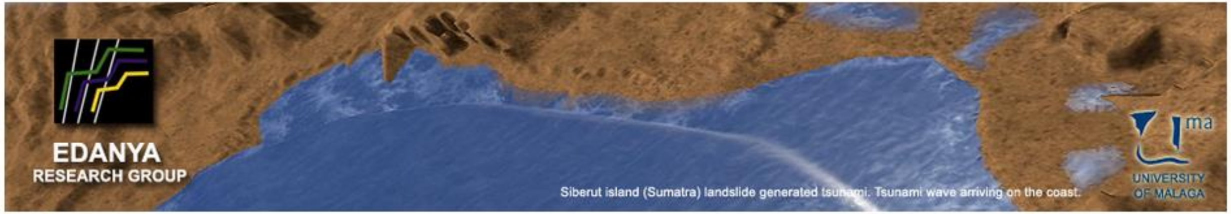
Probabilistic Tsunami Hazard Analysis

- Central component of PTHA workflow takes place in HPC facilities.
- Takes gridded seafloor deformation as initial condition.
- Propagation takes place on system of nested grids.



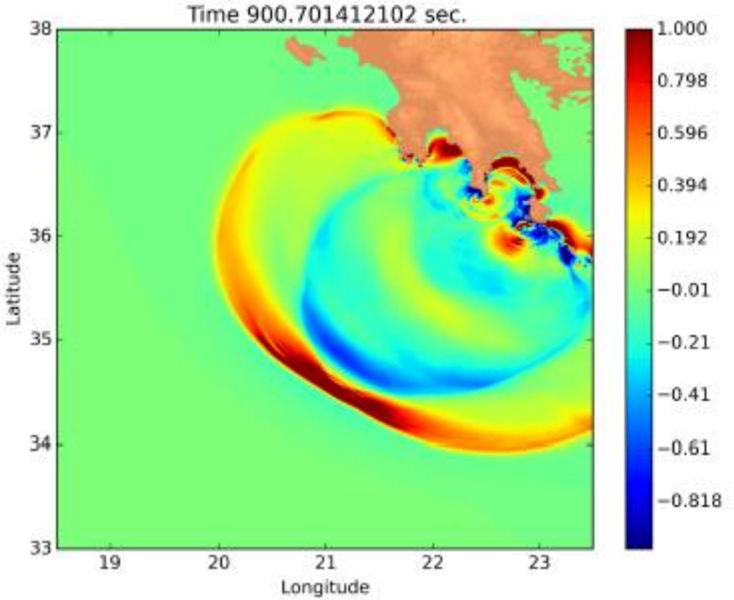
- Vast quantities of simulation output may be generated.
- Need to choose carefully exactly which outputs are needed.
- «Minimum» data in target region for ~10^5 scenarios → many TB

Numerical Tsunami Simulation



- Tsunami-HySEA code (Univ. Málaga)
- Shallow-water non-linear equation GPU-implementation (CUDA)
- Computational time dependent on spatial domain and resolution.

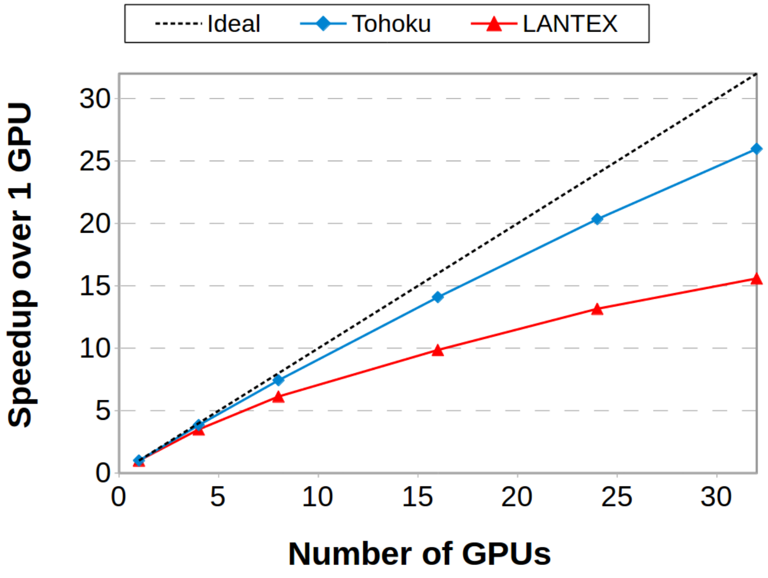
n. GPUs	Comput. time	Speed-up	#times FTRT
1	1181.51	1.00	18.28
2	672.35	1.76	32.13
4	396.70	2.98	54.45
8	221.31	5.34	97.60
12	200.78	5.88	107.58



https://edanya.uma.es/hysea/index.php/17-T_H-software-details

Numerical Tsunami Simulation

- Scalability very much a function of the physical domain.
- The Trans-Pacific (Tohoku) tsunami calculation on open ocean scales better than LANTEX (Large Atlantic Tsunami Exercise) – Caribbean source and inundation regions.



nGPUs	Tohoku			Lantex		
	Time (s)	Speedup	Efficiency	Time (s)	Speedup	Efficiency
1	7547.54	1.00	1.00	8108.44	1.00	1.00
4	1963.02	3.84	0.96	2313.60	3.50	0.88
8	1016.23	7.43	0.93	1322.52	6.13	0.77
16	535.64	14.09	0.88	822.57	9.86	0.62
24	371.01	20.34	0.85	616.11	13.16	0.55
32	290.64	25.97	0.81	520.16	15.59	0.49

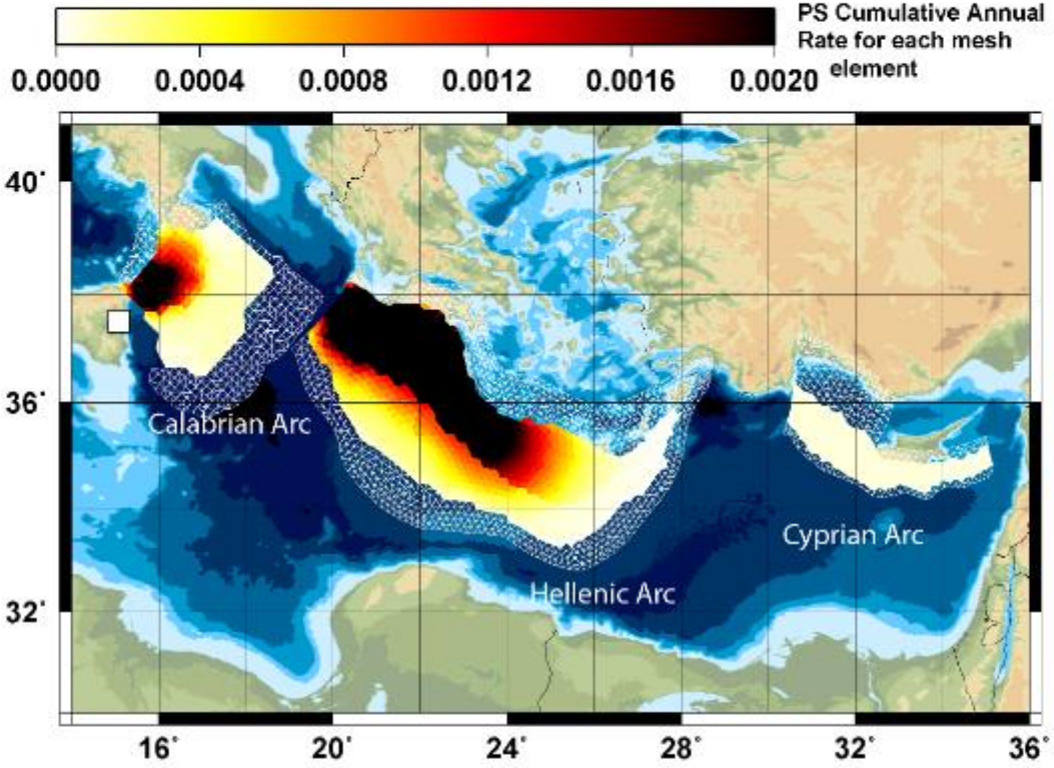
- In PTHA, we usually run it in «embarrassingly parallel» mode – there are so many scenarios to compute that it is most efficient to have one simulation per GPU.

Probabilistic Tsunami Hazard Analysis

In PTHA, in principle, we need to consider EVERY possible source of tsunami!

In practice, this can't be done – we need to discretize possible sources and perform **hazard disaggregation** (find which sources matter most).

We consider **Predominant Seismicity** (well understood subduction earthquakes)



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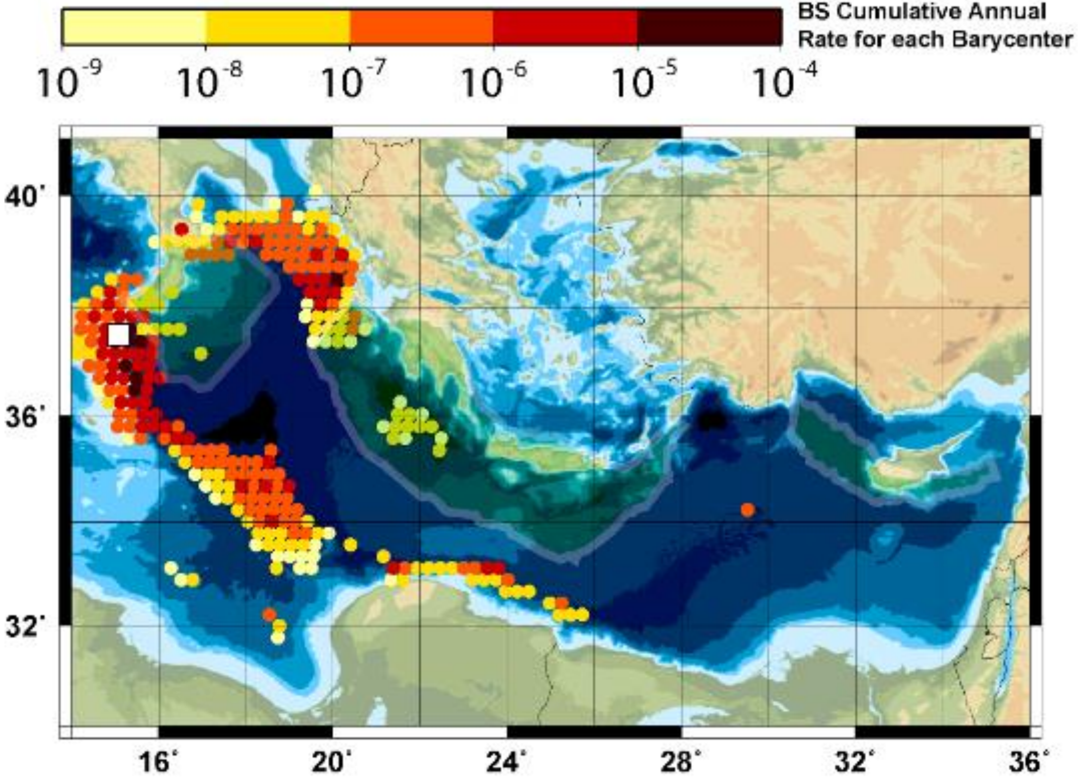
Probabilistic Tsunami Hazard Analysis

In PTHA, in principle, we need to consider EVERY possible source of tsunami!

In practice, this can't be done – we need to discretize possible sources and perform **hazard disaggregation** (find which sources matter most).

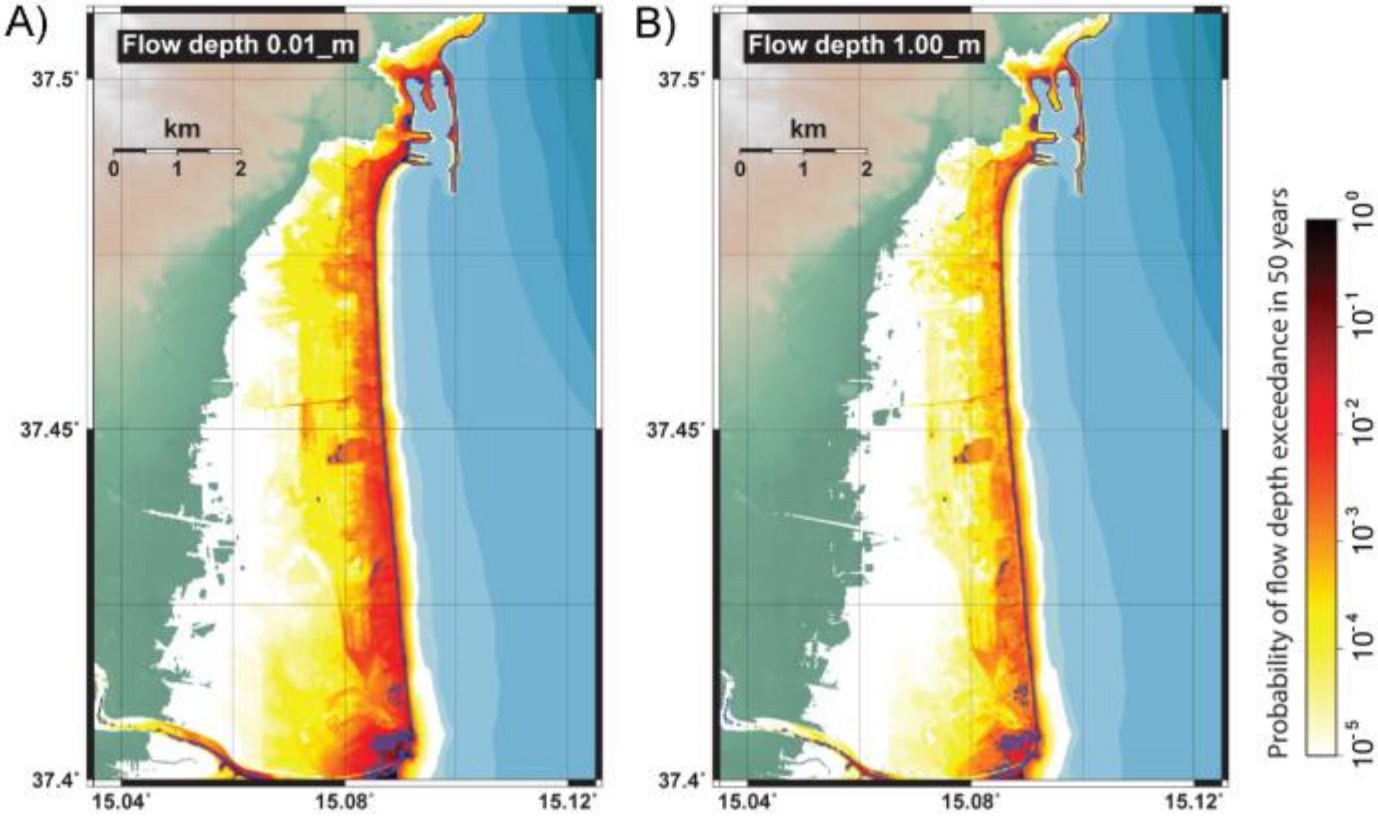
We consider also Background Seismicity (crustal earthquakes in poorly understood tectonic settings)



Probabilistic Tsunami Hazard Analysis

For the first time, we are able to generate high resolution inundation maps for single scenarios – and local scale hazard maps.

(33000 earthquake scenarios for Catania.)

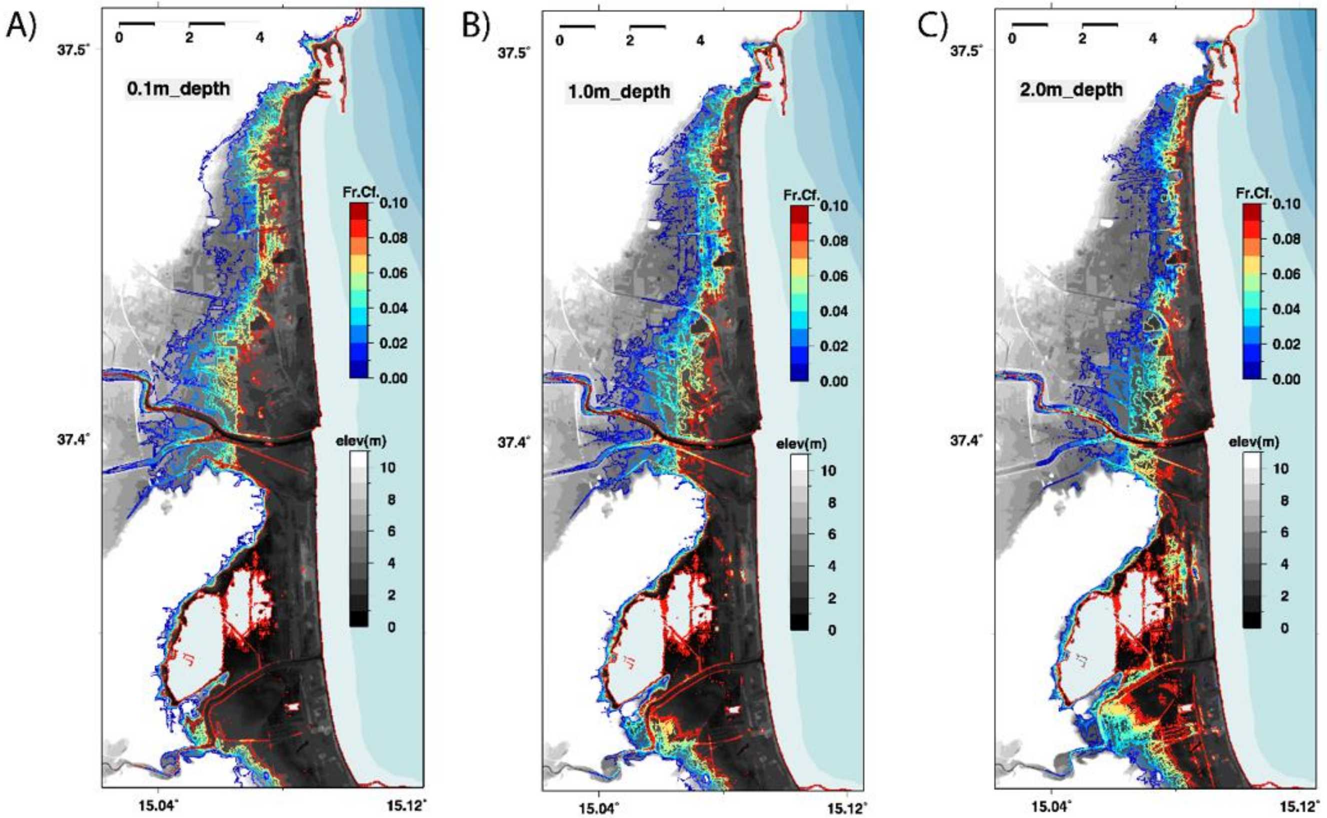


Probabilistic Tsunami Hazard Analysis

Sensitivity Studies allow us to see how the severity of tsunami inundation changes with details of the numerical model.

(Here, friction.)

This helps us quantify the uncertainty.

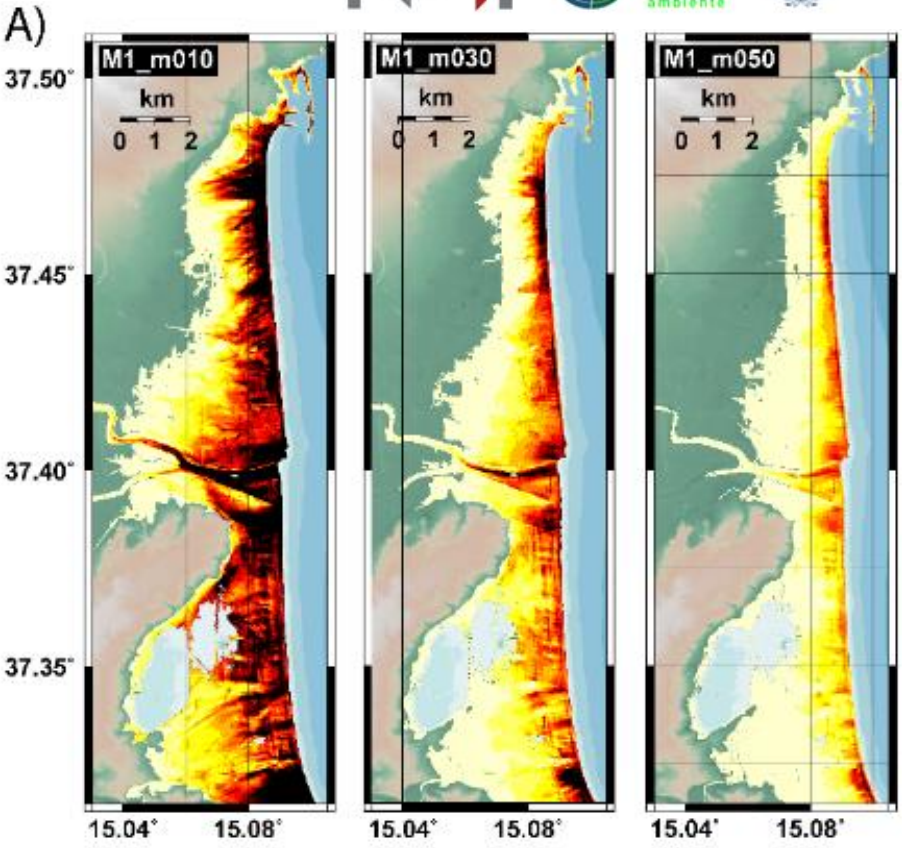


Probabilistic Tsunami Hazard Analysis

Sensitivity Studies allow us to see how the severity of tsunami inundation changes with details of the numerical model.

(Here, friction.)

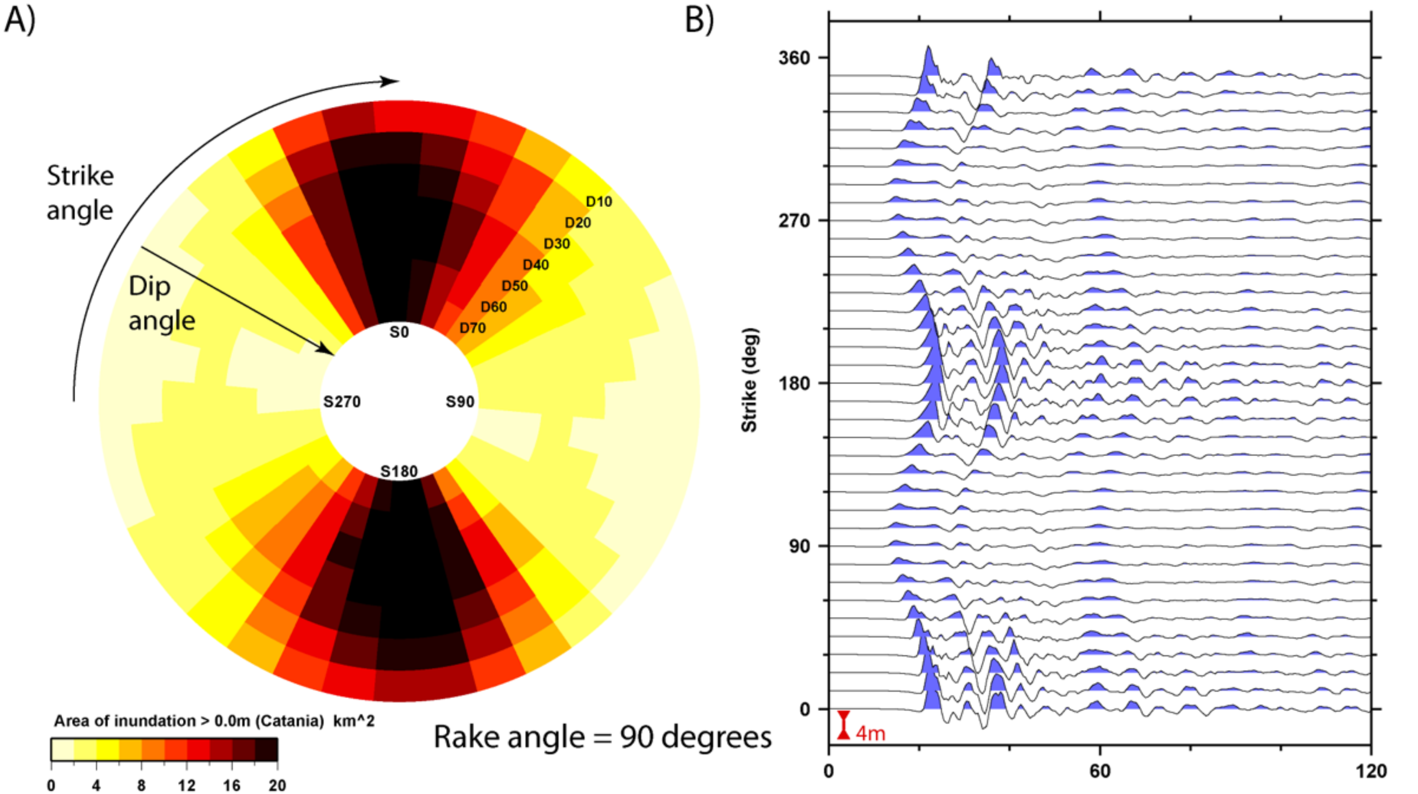
Maybe the momentum flux is a more important parameter? This varies with the friction more than the actual inundation depth.



Probabilistic Tsunami Hazard Analysis

Sensitivity Studies allow us to see how the severity of tsunami inundation changes with the earthquake parameters.

This guides our choice of earthquake scenarios for PTF and UrgentHPC.



Offshore Earthquakes

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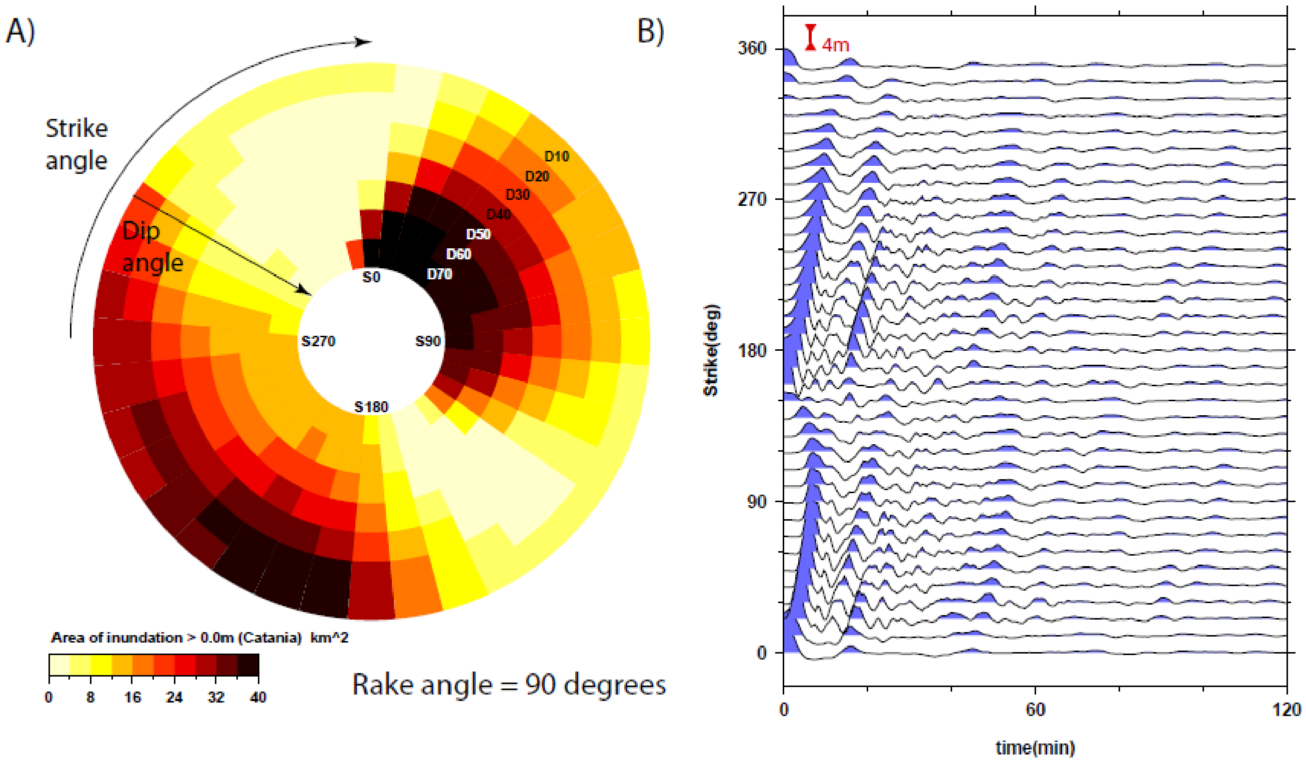
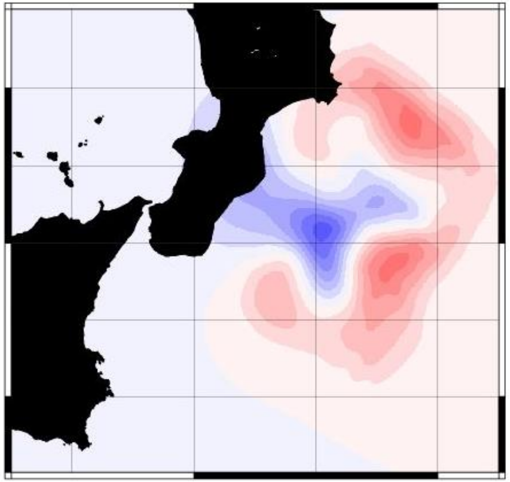


Near-Shore Earthquakes

Probabilistic Tsunami Hazard Analysis

PARTNERSHIP FOR ADVANCED COMPUTING IN EUROPE

- Additional computational resources made possible through a successful PRACE application.
- 70,000,000 core hours on Marconi-100 at CINECA, Rome between October 2020 and September 2021.
- A total of 608385 tsunami simulations so far!
  - 222560 simulations BS/Background Seismicity
  - 385823 simulations PS/Predominant Seismicity
  (all this in addition to previous PTHA calculations)
- Many possibilities using this new database:
  - Refined hazard aggregation
  - PTHA benchmark case – convergence testing
  - Many possibilities in sensitivity studies and machine learning.



Probabilistic Tsunami Hazard Analysis

Conclusions

- HPC now opens up the possibility of high-resolution local scale Probabilistic Tsunami Hazard Analysis.
- Previously only regional scale PTHA has been possible – or high resolution inundation for a few scenarios (usually Worst Case Scenarios)
- We are now testing the limits - ~1000000 scenarios in current PRACE award on the Marconi-100 cluster at CINECA, Rome.
- Extensive Sensitivity studies will help us understand the physics and help design better future PTHA.