


# High Performance Computing for Probabilistic Tsunami Hazard Analysis

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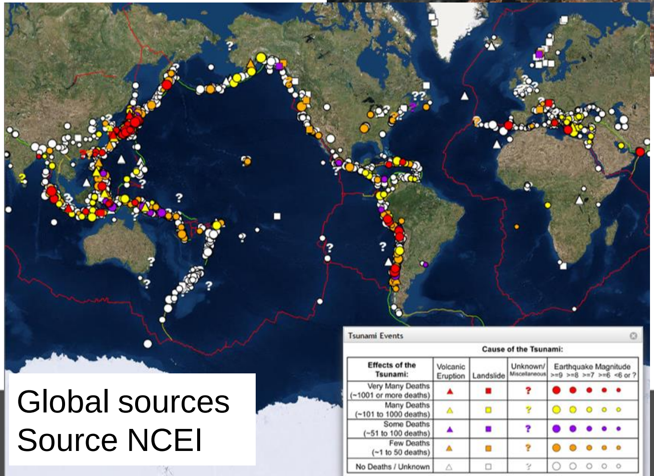
# Tsunami hazards

- About 80% of the global tsunami sources are earthquakes
- 10-20 events annually
- High impact events are infrequent
- Uncertainty driven hazard - large source uncertainty
- Data record too short for hazard assessment → Numerical models necessary for hazard analysis
- Wave propagation and wave physics key

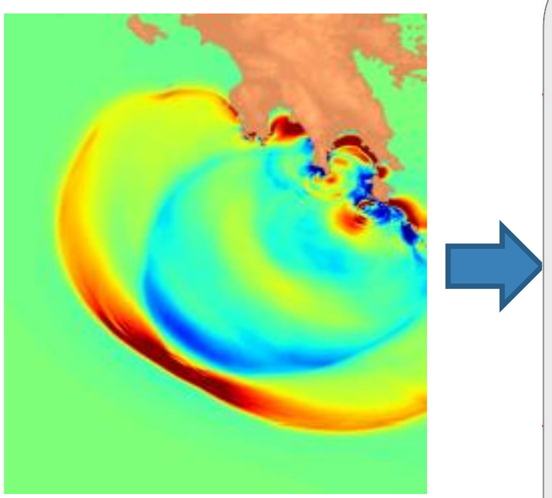


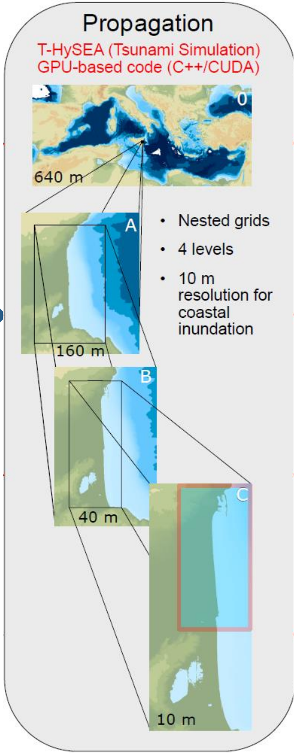


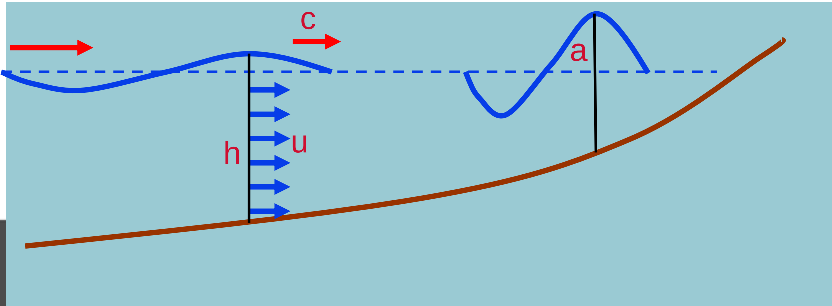

Global sources
Source NCEI

# Tsunami physics and hazard modelling

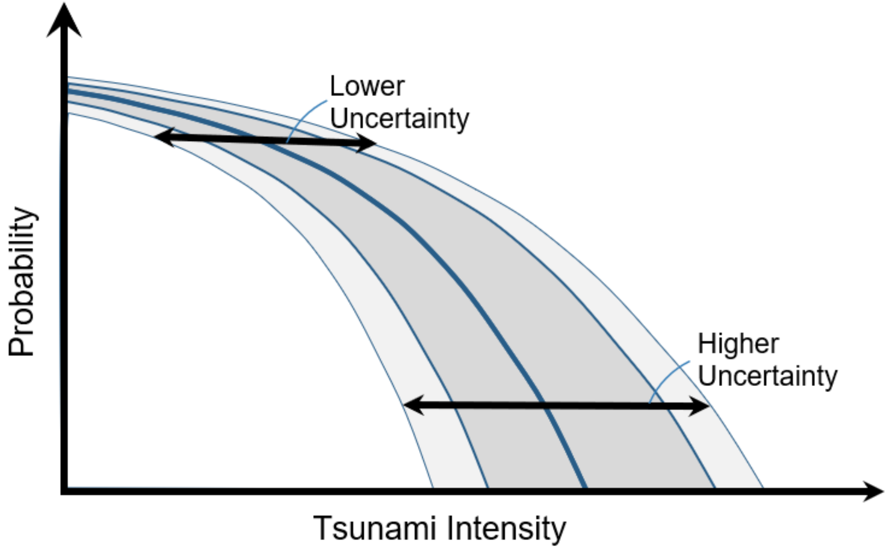
- Offshore propagation
  - Long waves small amplitude – large geographic scales
  - Coarse grid – simple wave physics – wave eq
- Nearshore and inundation
  - Short waves and high resolution grids
  - Non-linear – breaking and shock
  - Dry land inundation and friction
- **Shallow water type models**
  - Depth averaged Navier Stokes 2HD
  - Often accurate enough for earthquake tsunamis
  - Nested grids with different resolutions
- More advanced physics typically too expensive for resolving uncertainties
  - Boussinesq type models
  - Computational Fluid Dynamics 3D
  - ...





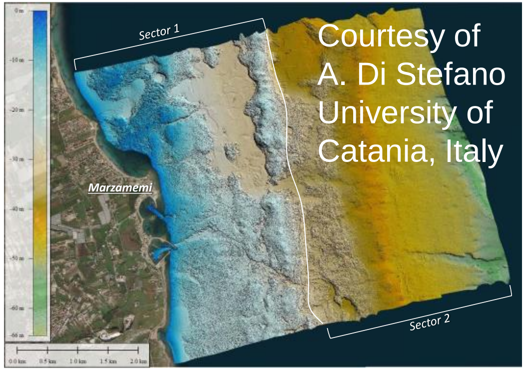



# Probabilistic Tsunami Hazard Analysis «PTHA»



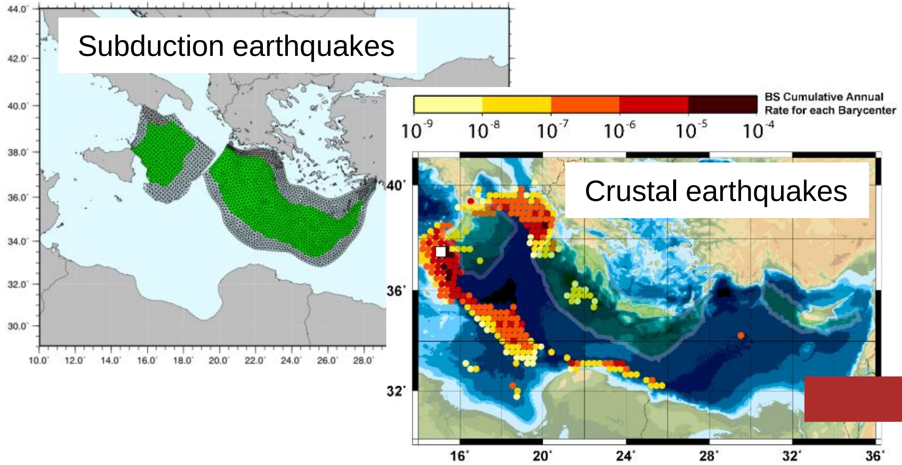

## Examples of Applications and Stakeholders

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

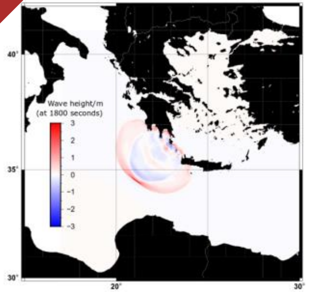



PTHA estimates the probability of exceeding a given tsunami inundation metric at a given location in a given time interval.

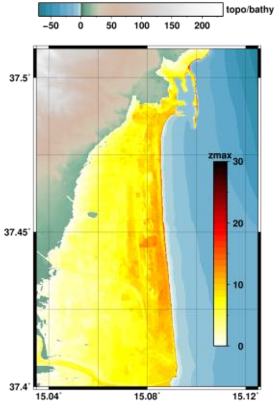
# Probabilistic Tsunami Hazard Analysis

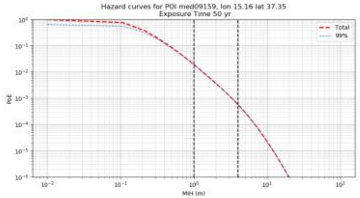



- Tsunamigenic earthquakes
- Vast number of «scenarios»
- Different mechanisms
  - Subduction earthquakes → Predominant seismicity (PS)
  - Crustal earthquakes that may occur «anywhere» → Background seismicity (BS)




- Tsunami simulation
- O($10^3$-$10^6$) of simulations →HPC required!



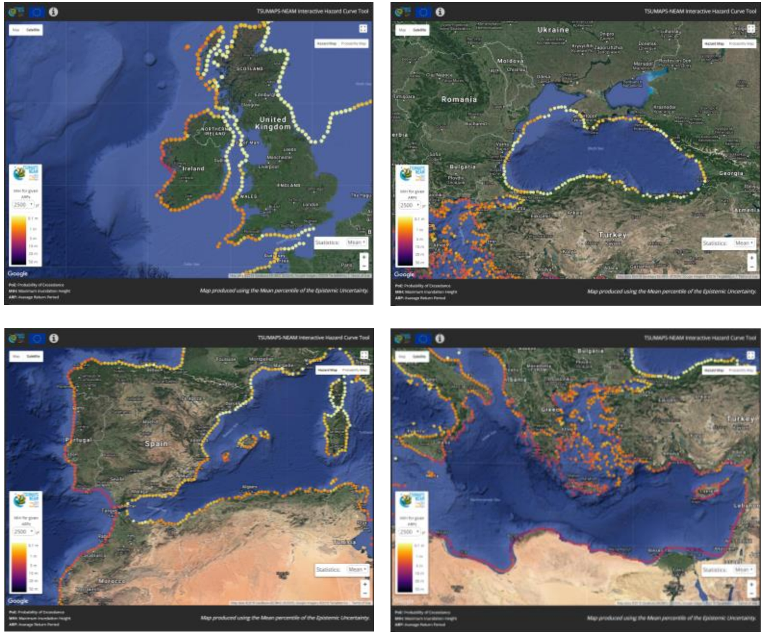




- Hazard aggregation
- Visualization

# Previous PTHA - TSUMAPS-NEAM

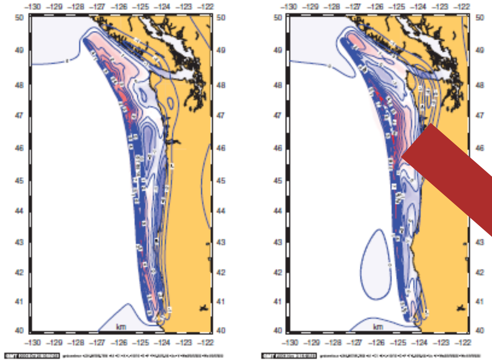
TSUMAPS NEAM
Probabilistic TSUnami Hazard MAPS for the NEAM Region

- Conducted in **NEAM**: North East Atlantic and Mediterranean Sea
- Regional / coarse grained assessment – earthquake sources
- Contains assessment of rates, community treatment of epistemic uncertainty
- Offshore simulations only
- Local inundation roughly approximated
- Local hazard not available → Computationally intensive → For local high resolution simulations, large HPC resources are needed



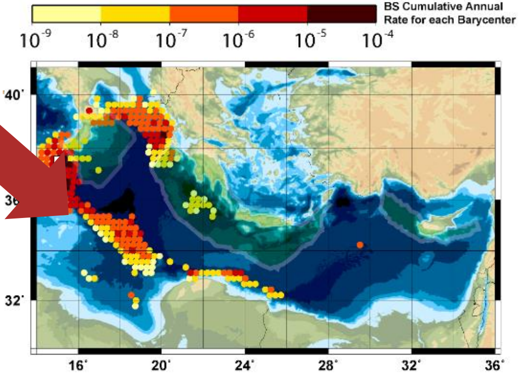
# Probabilistic Tsunami Hazard Analysis

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



Gonzalez et al. 2009, JGR ~25 sources

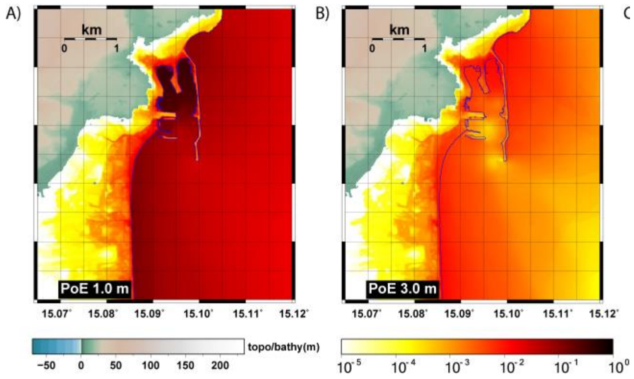
Gibbons et al. 2020, Frontiers Earth Sci.
~33000 sources

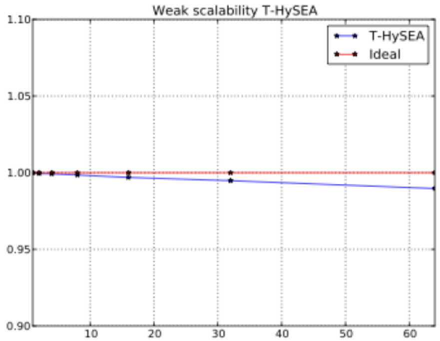



- **ChEESE – high resolution inundation calculations - From regional to local hazard**
- **Local tsunami hazard based in the NEAM – future community service**
- **Increase from a handful of tsunami sources to $10^4$-$10^5$ sources for inundation runs**
- **HPC can provide much more fine grain source uncertainty treatment than previous studies as the source number is highly increased**
- **Benchmark PTHA and understand how elaborate source uncertainty treatment needs to be**

# Efficient GPU shallow water models key to efficient modelling – Tsunami HySEA

- Highly efficient Shallow water solver using GPUs (CUDA implementation)
- Implemented using FV, Riemann solvers
- Include nested grid facilities
- Optimized for both single run and embarrassing parallelism
- Efficient weak scalability – simulations at large scale tested at Marconi100 up to ~1000 GPUs
- More details in next talks

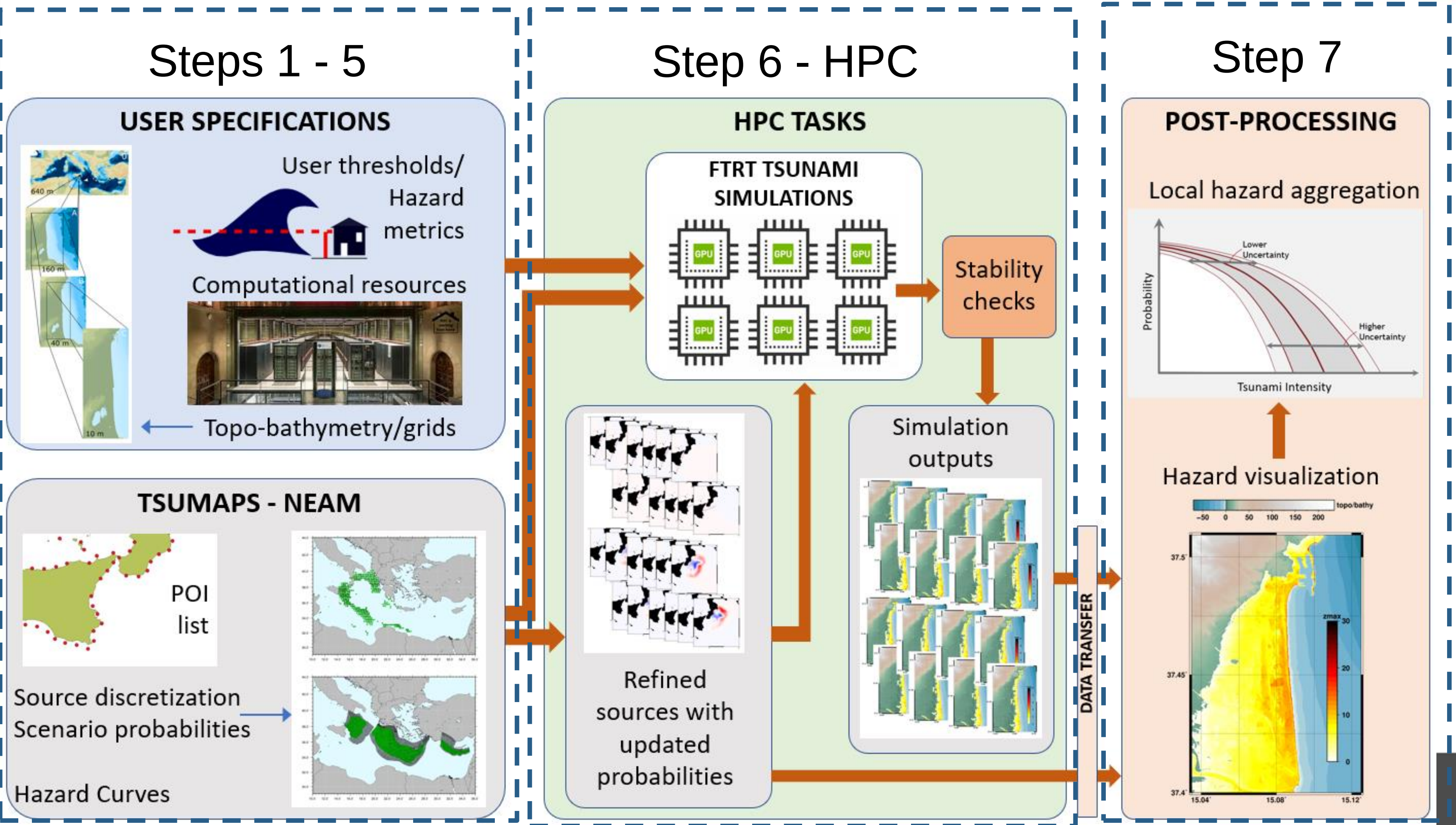


# Probabilistic Tsunami Hazard Analysis
## 7 Step workflow procedure

| Step 1 | Step 2 | Step 3 | Step 4 | Step 5 | Step 6 | Step 7 |
|---|---|---|---|---|---|---|
| Select Study region | First order source screening | Scenario Disaggre-gation | Scenario rates | Scenario refinement | Tsunami simulations | Hazard aggregation |

# Probabilistic Tsunami Hazard Analysis



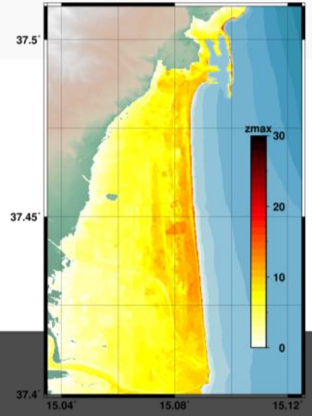
# Probabilistic Tsunami Hazard Analysis

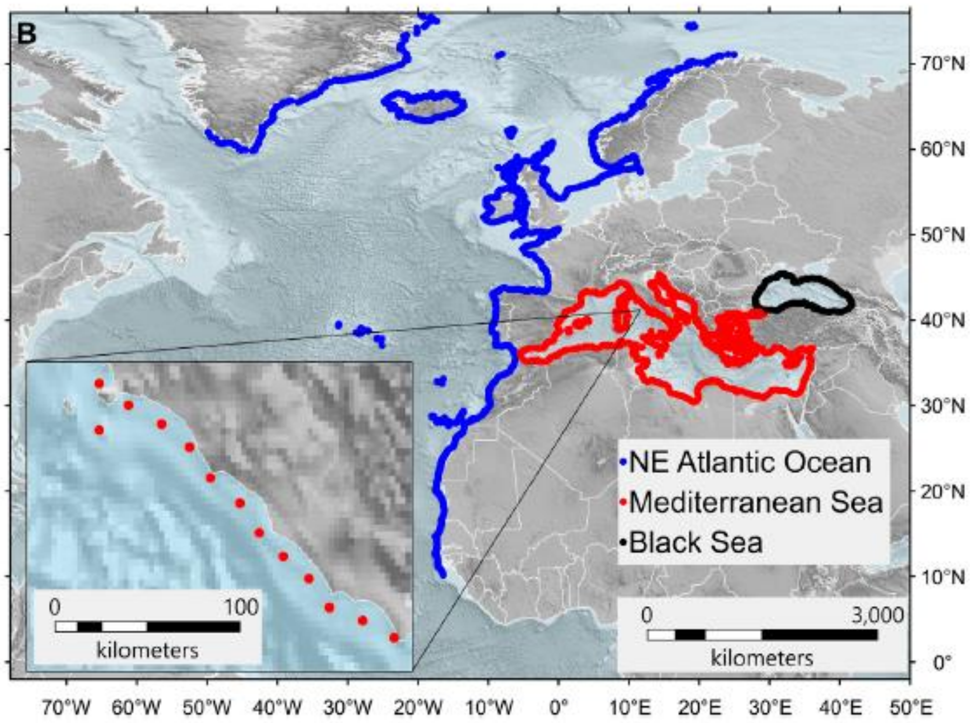
Step 1

Select Study region

The TSUMAPS tsunami hazard model - a set of nearshore POIs - «Points of Interest».

POIs should coincide with the high resolution grids to be used for local inundation:



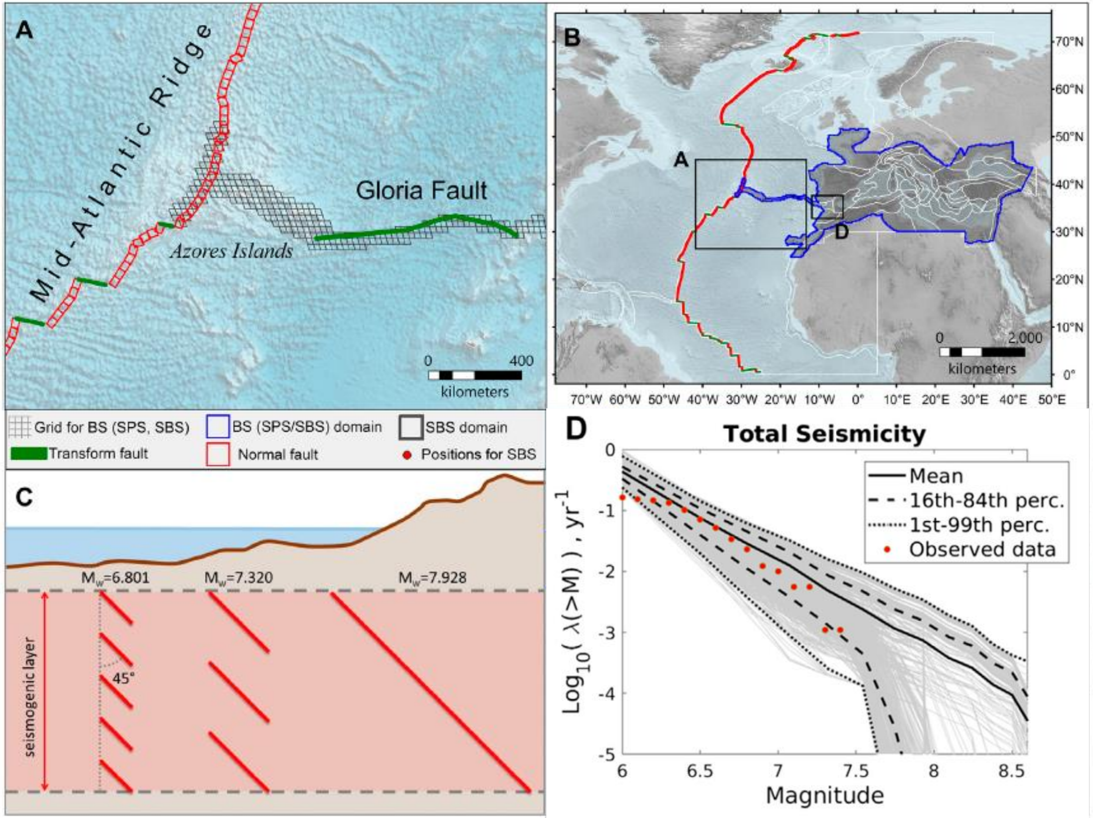



# Probabilistic Tsunami Hazard Analysis

Step 1 — Select Study region

**Step 2 — First order source screening**

Step 3




Preconditioning - branch of the potentially relevant scenarios - associated metadata (earthquake mechanisms, extent, and probabilities)

# Probabilistic Tsunami Hazard Analysis

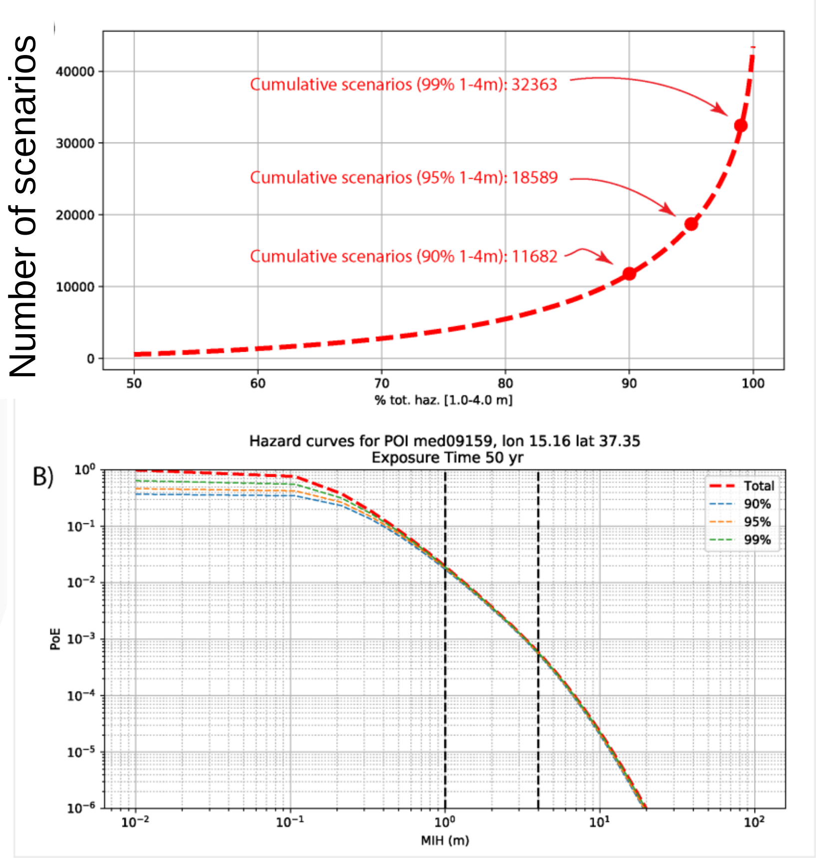
Step 1 Step 2 **Step 3** Step 4

Scenario Disaggre-gation

How many scenarios we need to reproduce the required hazard level

More accuracy – more computational resources

Use mean probabilities as input to disaggregation



# Probabilistic Tsunami Hazard Analysis

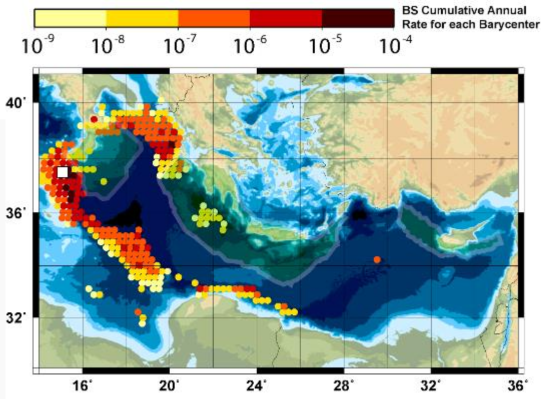
Step 1 — Select TSUMAPS POIs

Step 2 — First order source screening

Step 3 — Scenario Disaggre-gation

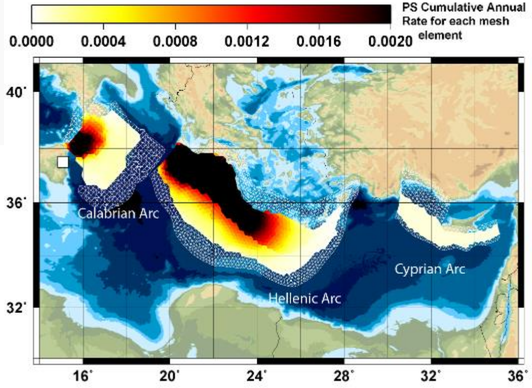
Step

The maps to the right show the earthquake sources that dominate the tsunami hazard at the town of Catania (Sicily, Italy)



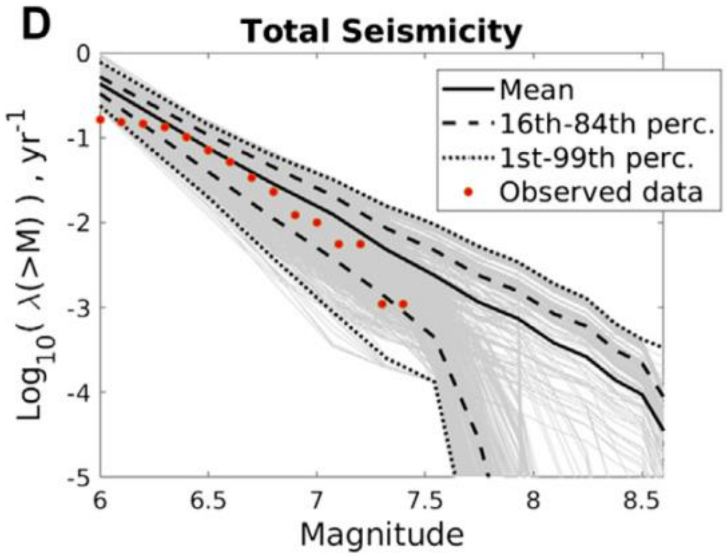

The earthquake scenarios that contribute most to the tsunami hazard at the specified location based on TSUMAPS (offshore)

Sources split into predominant (subduction) and background (crustal) sources

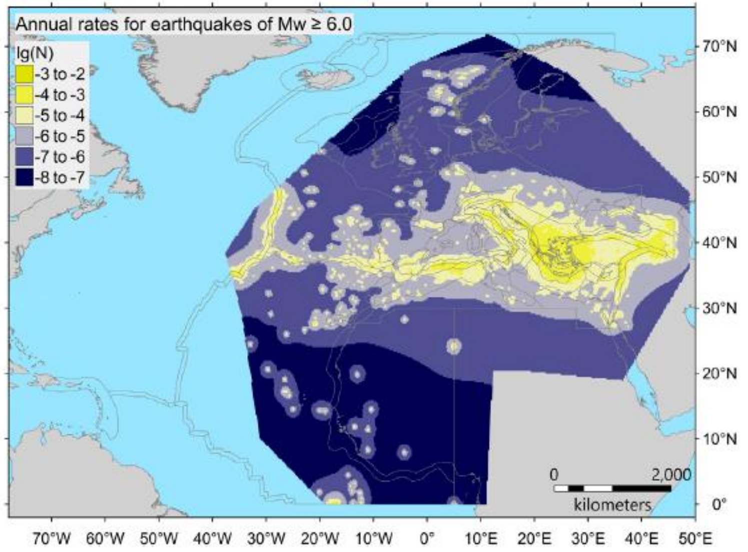


# Probabilistic Tsunami Hazard Analysis

Step 4



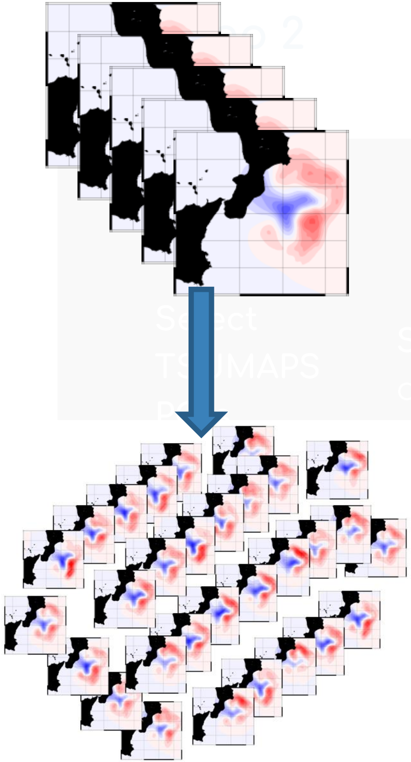

Scenario rates



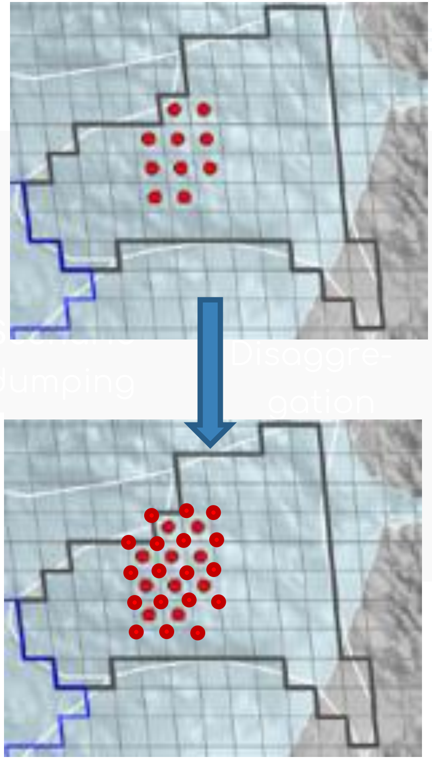

Earthquake rates for a given area as a function of moment magnitude

Rates are area dependent – and were preset in the TSUMAPS-NEAM assessment

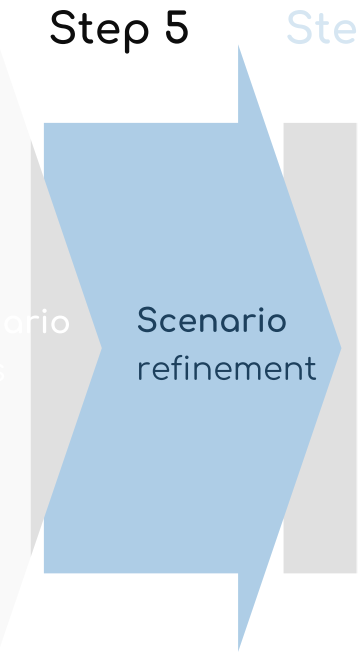
# Probabilistic Tsunami Hazard Analysis



Subduction zones
Stochastic slip



Crustal sources



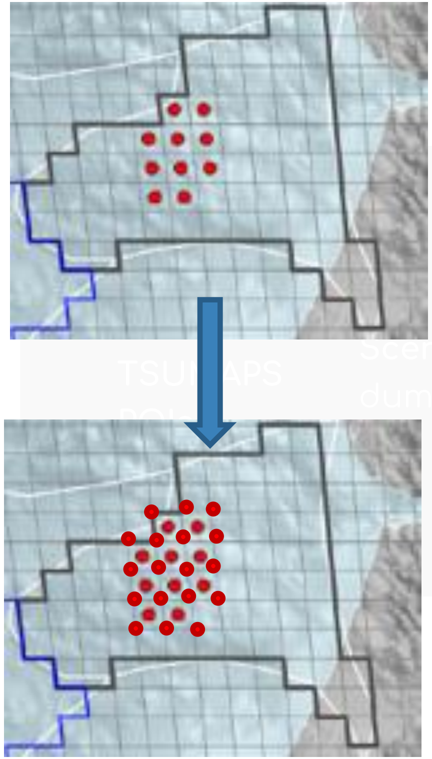

Increasing the number of sources:

Refinement of earthquake fault centers (epicenters)

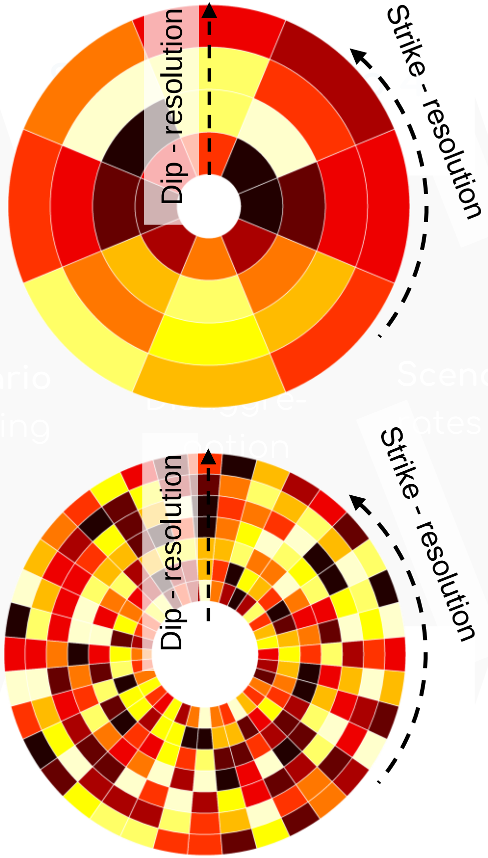
Increasing the number of slip realisations

Important for local hazard

# Probabilistic Tsunami Hazard Analysis



Epicenter locations




Focal mechanism

Step 5

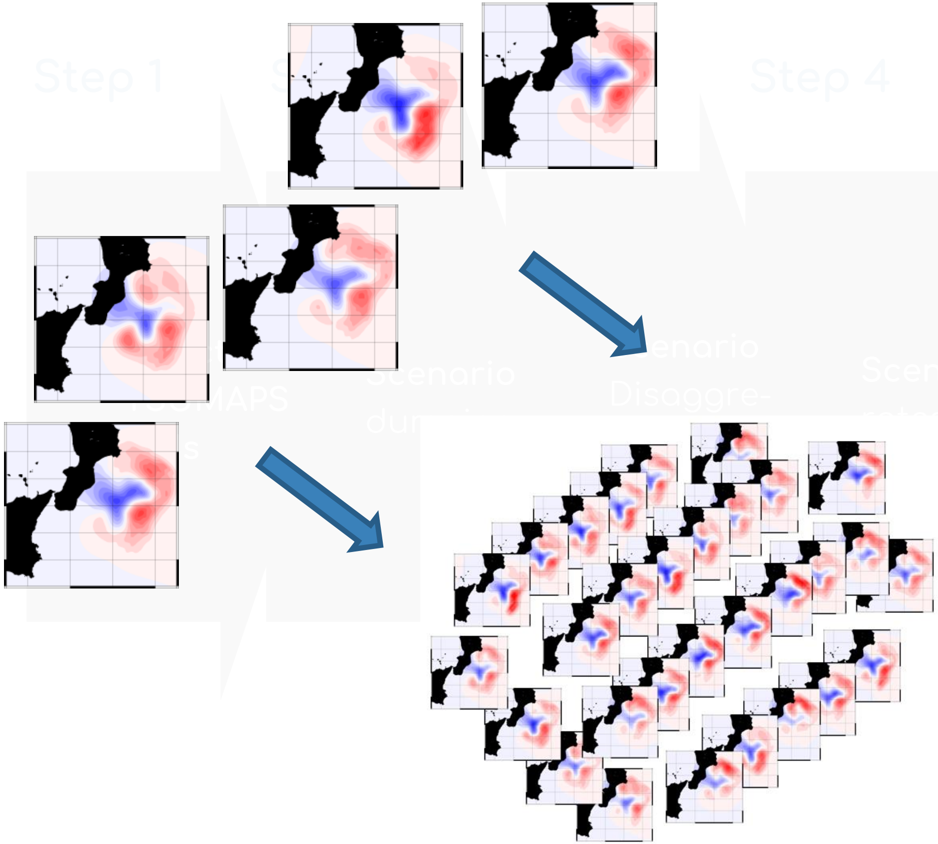
Scenario refinement

Refinement of crustal source parameters

Epicenter locations

Focal mechanism (angles of strike, dip, and rake)

# Probabilistic Tsunami Hazard Analysis



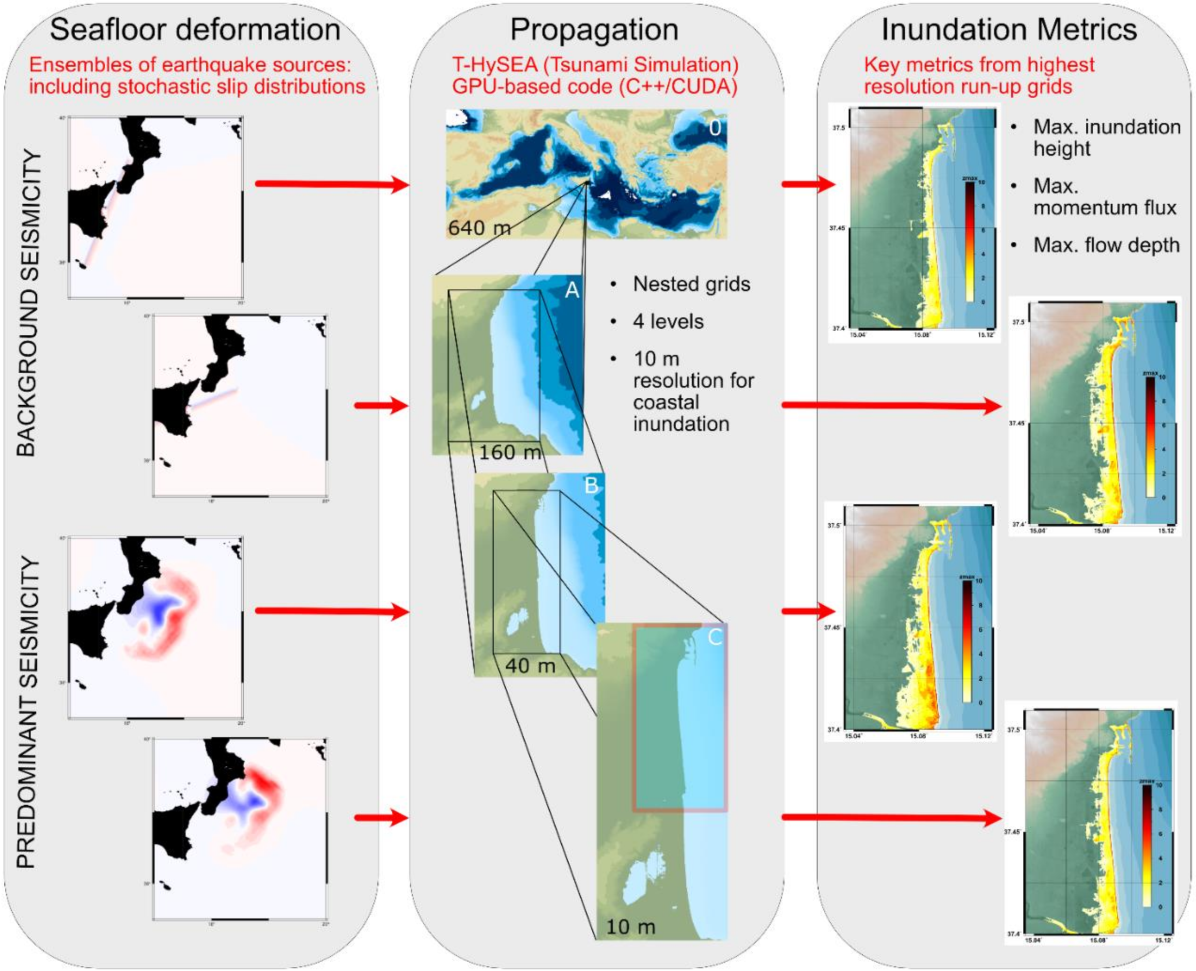
Step 5

Scenario refinement

Refinement of subduction zone earthquakes sources:

Increasing the number of stochastic slip distributions

# Probabilistic Tsunami Hazard Analysis




Step 6 Step 7

o ent | Tsunami simulations | Hazard aggregation

Each simulation takes ~30 min to calculate.
10 m local grids
High resolution grid most resource intensive (~2M points)

# Probabilistic Tsunami Hazard Analysis - Step 7

Sum probabilities and calculated hazard curves

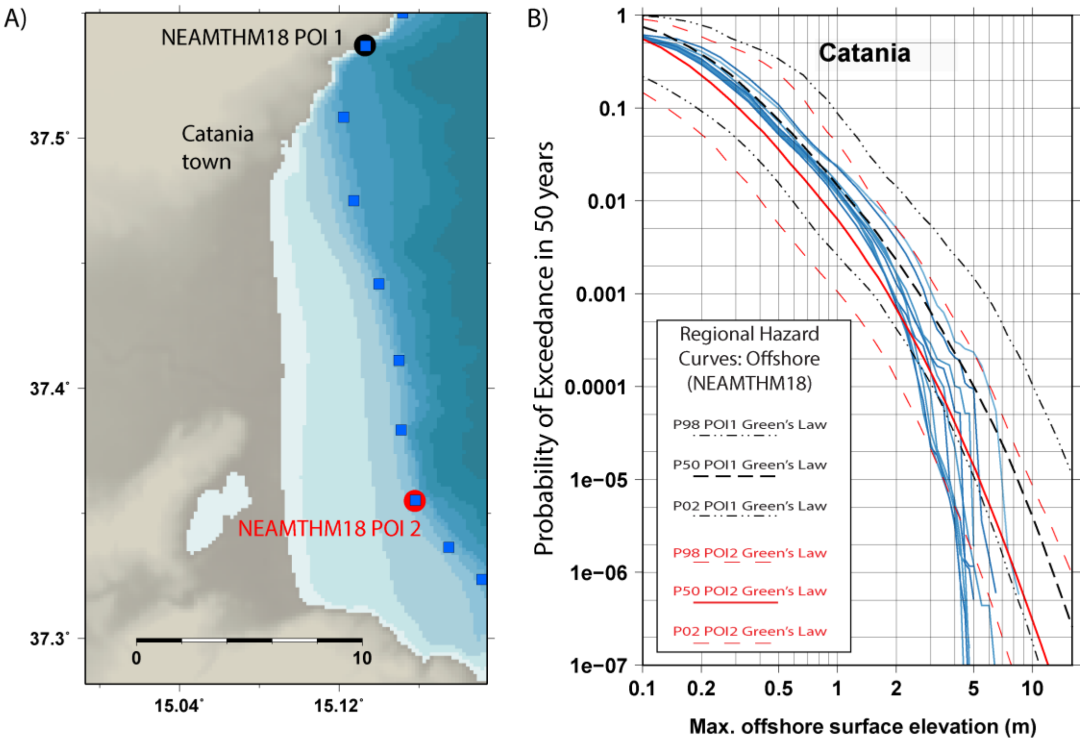
- All scenarios
- All seismicity types
- Assume Poissonean process

Calculate uncertainties by sampling epistemic uncertainties

$$\lambda(>MIH_{th})_{POI} = \sum_i \lambda(\sigma_i)\, P(>MIH_{th}|\sigma_i)_{POI}$$

$$= \sum_j \sum_k \lambda\left(\sigma_k^{(Type_j)}\right) P\left(>MIH_{th}\middle|\sigma_k^{(Type_j)}\right)_{POI}$$

$$P(>MIH_{th}, 50\,\mathrm{yr})_{POI} = 1 - \exp(-\lambda(>MIH_{th})_{POI} \cdot 50)$$



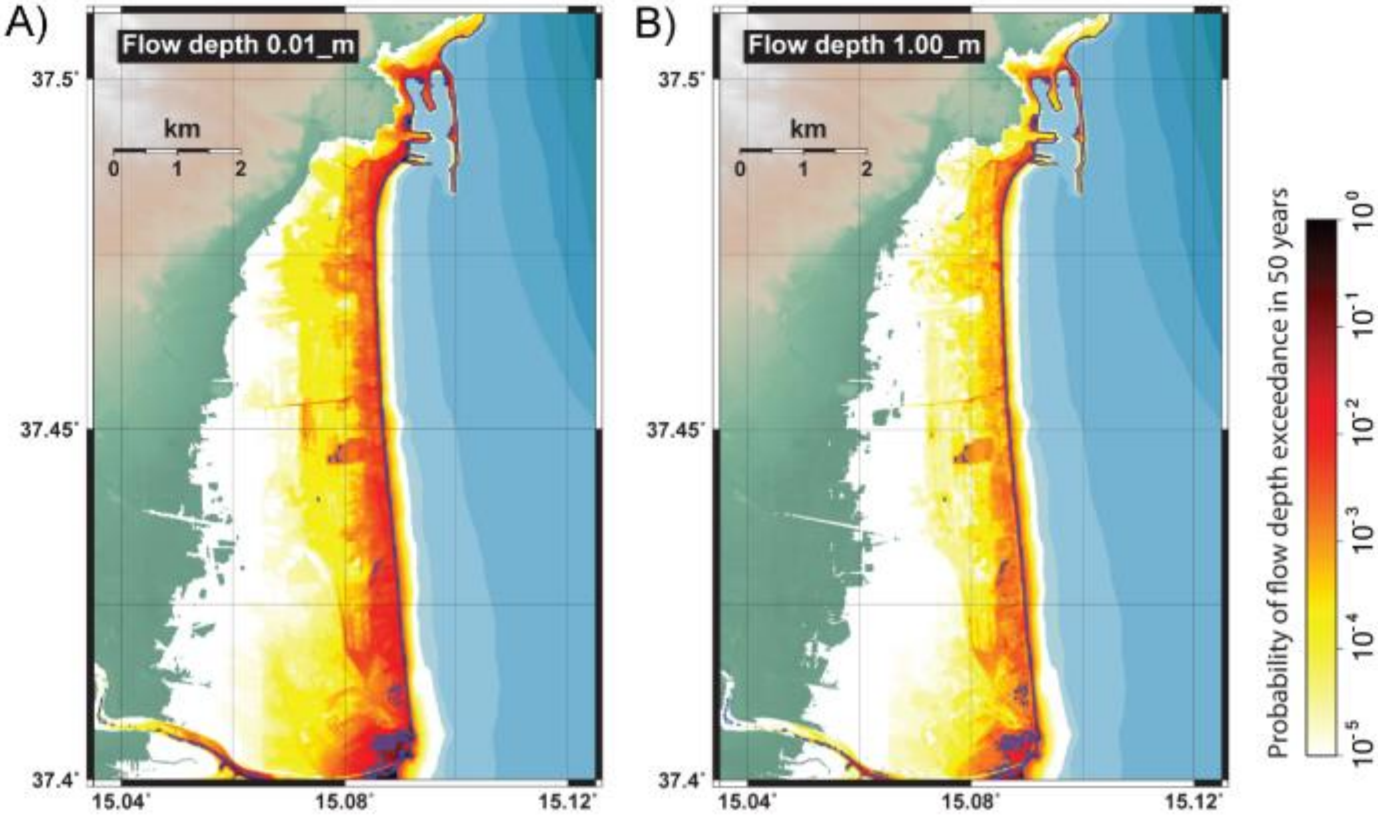

NGI INGV terremoti vulcani ambiente ChEESE

# Probabilistic Tsunami Hazard Analysis - Step 7

The efficient workflows allow us to generate high resolution hazard maps (exceedance probabilities)

Order of magnitude higher number of scenarios compared to previous work

Here – for 33000 earthquake scenarios for Catania.



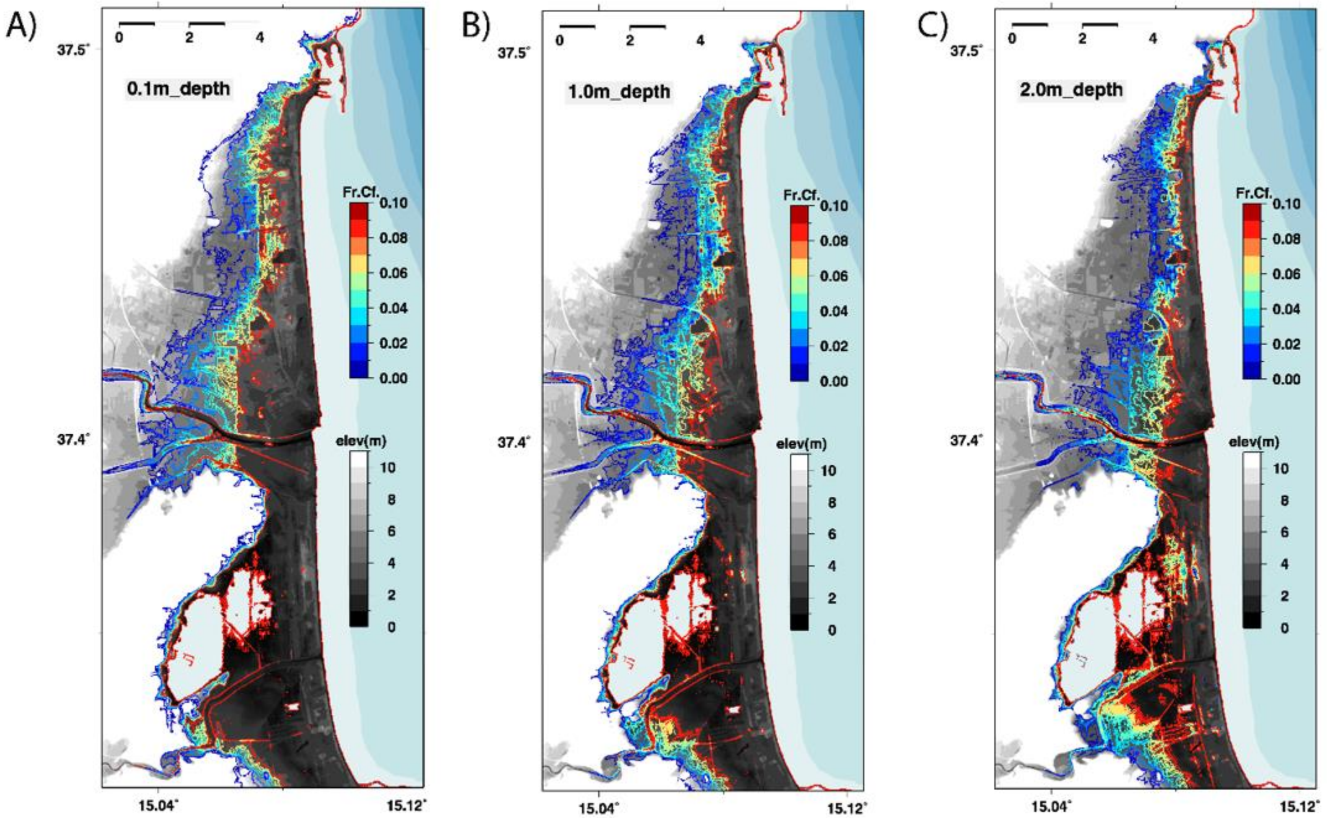

ChEESE

# Probabilistic Tsunami Hazard Analysis – spin off products

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

(Here, friction.)

This helps us understand which parameters that matters most for the uncertainty




ChEESE

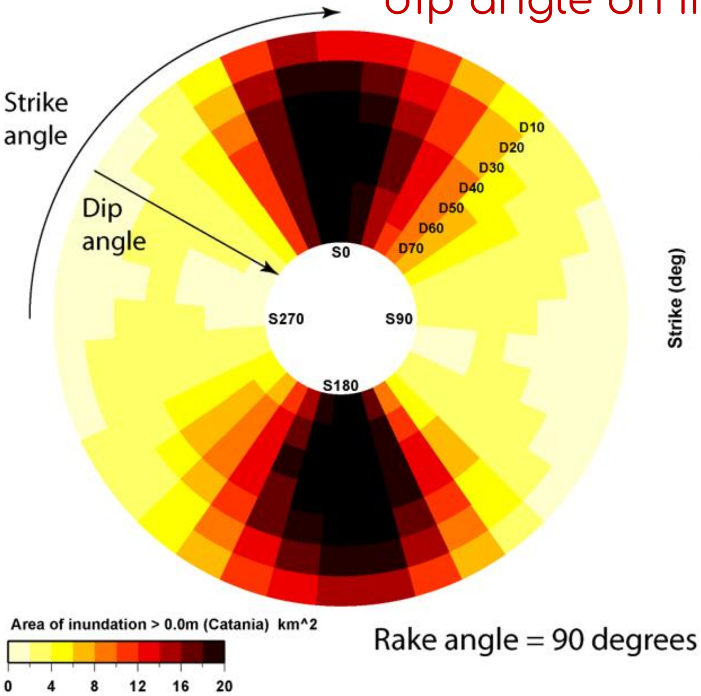
# Probabilistic Tsunami Hazard Analysis – spin off products

**Sensitivity Studies** allow us to see how the severity of tsunami inundation changes with focal mechanism parameters

Here focal mechanisms

Effect of earthquake strike and dip angle on inundated area

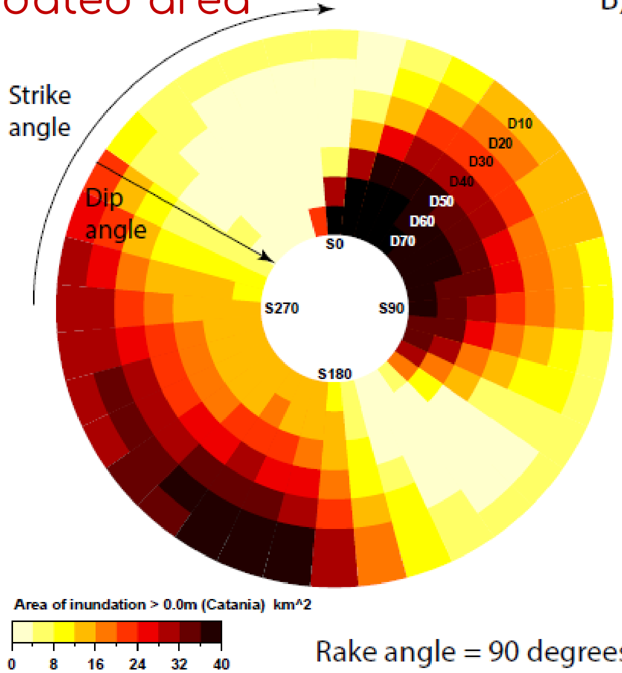
A)




Rake angle = 90 degrees

Far field earthquakes

B)




Rake angle = 90 degrees

Near field earthquakes

# Probabilistic Tsunami Hazard Analysis

PRACE PARTNERSHIP FOR ADVANCED COMPUTING IN EUROPE

- Additional computational resources made possible through the PRACE project TsuHazAP
- ~800 000 GPU hours on Marconi-100
- A total of 608385 tsunami simulations so far!
  - 222560 simulations BS/Background Seismicity
  - 385823 simulations PS/Predominant Seismicity
- ***New benchmark data for PTHA testing***
- Results yet to be analysed…

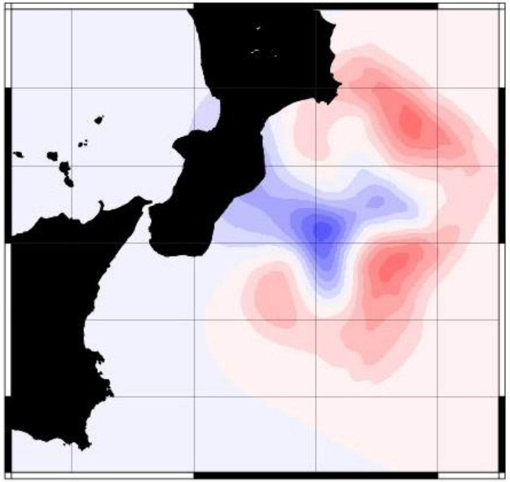

Marconi100 - 32 Pflop/s ~4000 GPUs
PTHA Workflow uses maximum resource
Granted by PRACE - ¼ of full capacity – 1000 GPUs

# Probabilistic Tsunami Hazard Analysis
## Future opportunities

PRACE PARTNERSHIP FOR ADVANCED COMPUTING IN EUROPE

eFlows4HPC

- Many possibilities using the new database:
  - Refined hazard aggregation
  - PTHA benchmark case – convergence testing
  - Many possibilities in sensitivity studies
- Use the large data bank for Machine Learning
- Operationalize data management and hazard aggregation – improved workflow management and High Performance Data Analytics (HDPA)
- Future tsunami service for PTHA – where users can upload own grids and do local hazard studies



# 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 limited number of 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.

***Key literature:***
Basili et al. (2021) Frontiers in Earth Science
https://doi.org/10.3389/feart.2020.616594
Gibbons et al. (2020) Frontiers in Earth Science
https://doi.org/10.3389/feart.2020.591549
Tonini et al. (2021) Frontiers in Earth Science
https://doi.org/10.3389/feart.2021.628061