Tsunami modeling up to coastal impact, operational challenges and uncertainties

Audrey Gailler

Montpellier, 30/06/2025

Coastwave2.0 Project Workshop

Context

R&D in Tsunamis at CEA/DAM

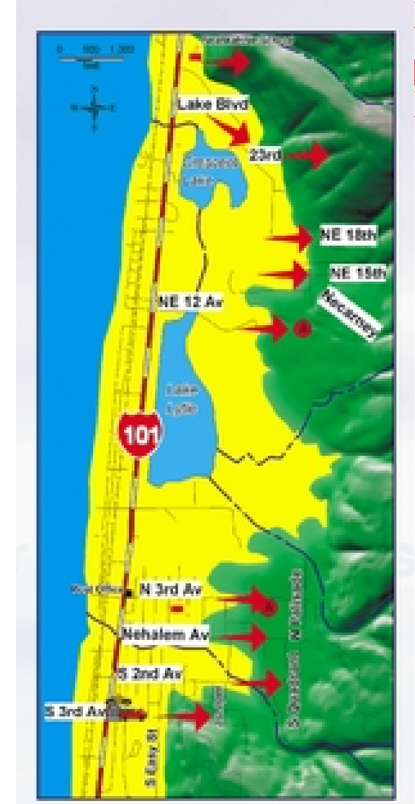
- Since the 60s : Activities in French Polynesia
- Since the 90s : European dynamics for tsunami research, involvement of CEA in **European projects** (GITEC)
- Since **2004,** then **2011** : New framework
  - Implementation of warning centers => CENALT at CEA
  - European projects (FP6, FP7, H2020-Euratom)
  - **projects funded by ANR, PIA** (TSUMOD, MAREMOTI, TANDEM)

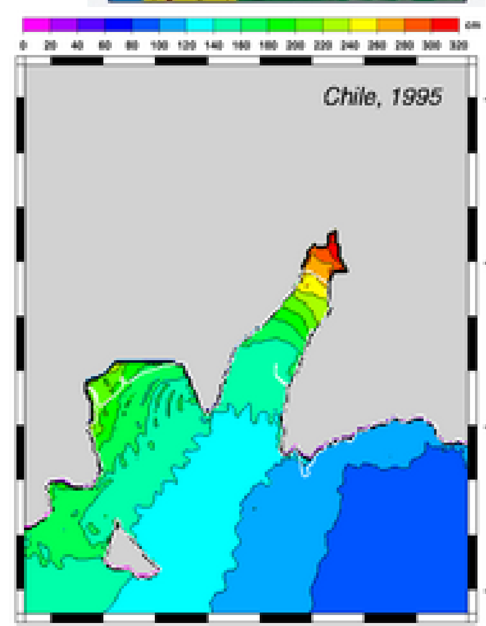
Current issues

- More advanced **hazard assessment studies** (very high resolution data, parametric approaches, knowledge of historical cases)
- Operational applications : the **real time forecasting** of coastal effects
- Projects :
  - **PIA TANDEM, H202-Euratom NARSIS** (Post Tohoku 2011/ impact on coastal nuclear facilities)
  - **ANR CarQUakes** (Lesser Antilles)**, ANR Amorgos** (Greece)

Tsunami modeling: what for?

- Modeling - and comparing it with observables - makes it possible to :
  - Validate codes
  - explain the phenomenon
  - constrain the source





- Answer the questions:
  - where to install infrastructure?
    => flood maps
  - how to manage the event?
    => evacuation mapping

- **Tsunami warning component**

CEA/DAM Tsunami modeling codes

Earthquake-origin tsunami :
Taitoko

- HPC model (fortran 2003)
- Earthquake initiation following Okada formula
- StVenant + Boussinesq equations
- Nested grids + Multibranch

Landslide-origin tsunami :
Avalanche

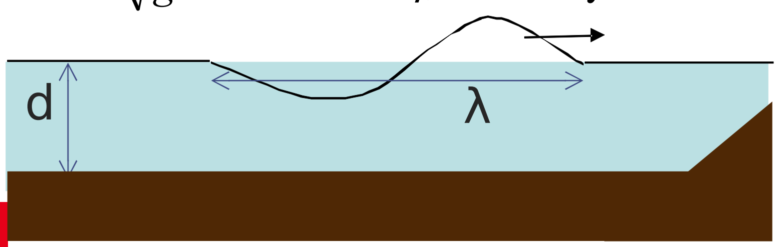
- Parallelized model (fortran 90)
- Landslide considered as a granual flow under the action of gravity (Coulomb-type law)
- StVenant + Boussinesq equations
- Nested grids

Strong earthquakes (magnitude > 7)

Saint-Venant : λ >>d

ε=η/d non negligible
u= uniform horizontal velocity

$c = \sqrt{gd}$ $h=d+\eta$, c=celerity

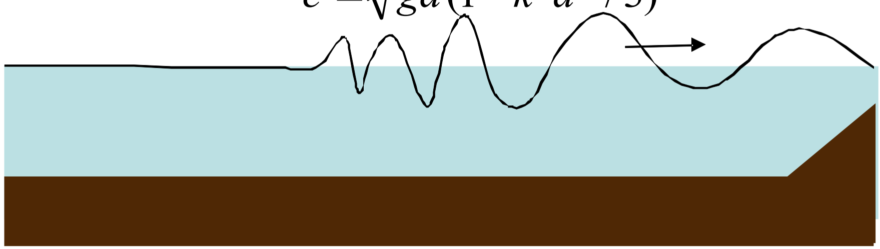


Moderate earthquakes (magnitude < 7) or landslides

Boussinesq : λ < 10 d

Take into account dispersion effects

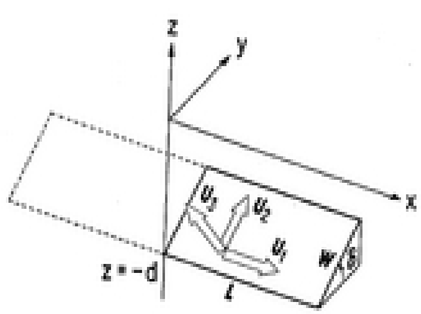
$c = \sqrt{gd(1 - k^2 d^2 / 3)}$



Tsunami Modeling Using Taitoko Code

Earthquake triggering (Okada formula- 1985)

- Deformation of the seabed is induced by uniform sliding on a rectangular fault in an elastic, isotropic and homogeneous medium.
- Ground movement is transmitted instantaneously to the water column above the source



Wave Propagation (Shallow water equations)

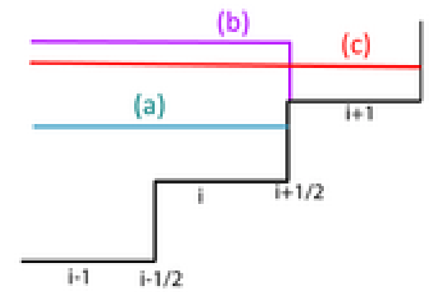
- λ(*tsunami*) > depth h

$$c \sim \sqrt{gh}$$

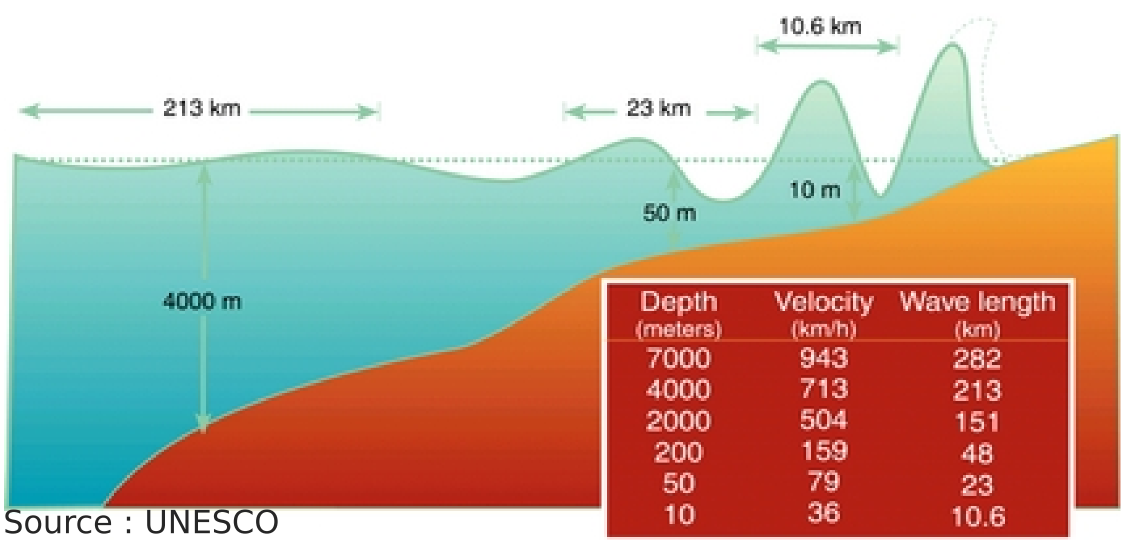
- **Shallow-Water** equations: development of the **1D Saint-Venant** equations
- **Boussinesq** equations: taking account of dispersion effects

Coastal flooding

Needs high resolution topo-bathymetric grids



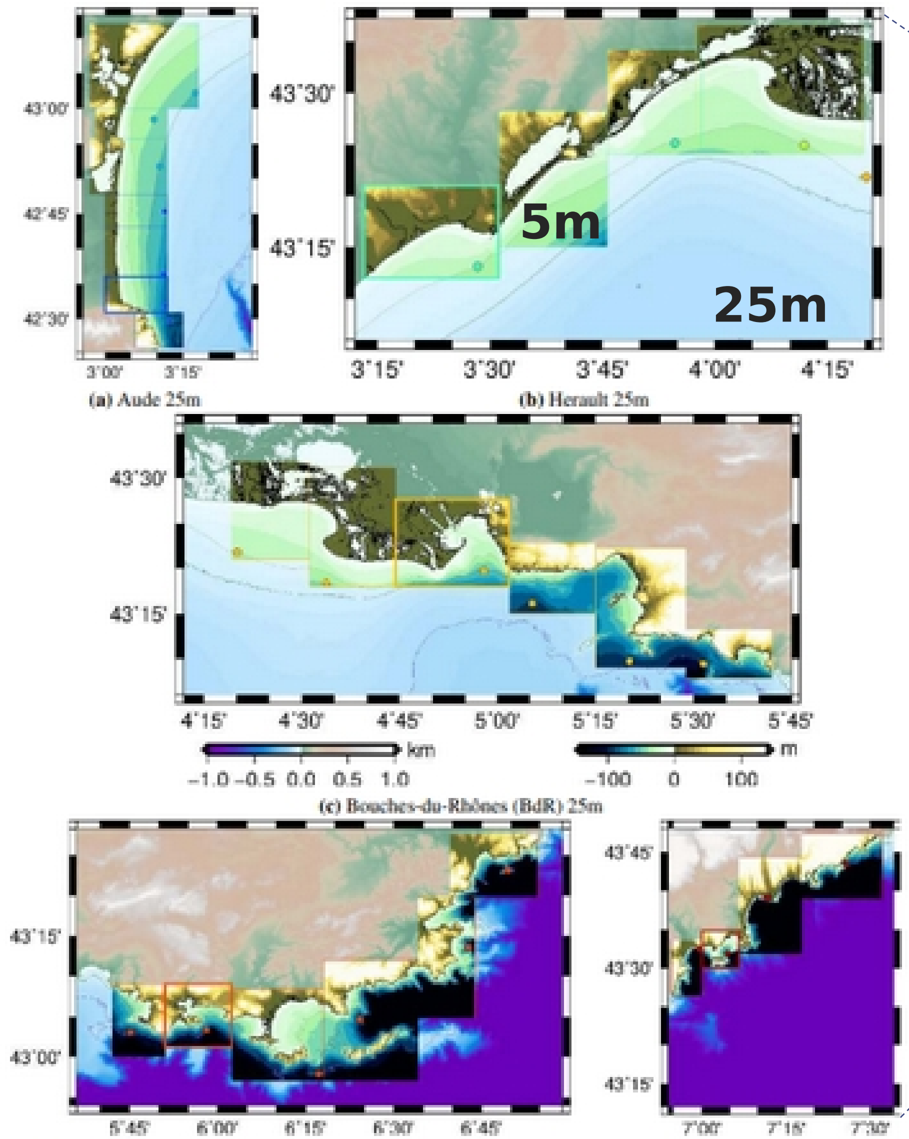
Taitoko code developed at CEA (Heinrich et al., 2021)

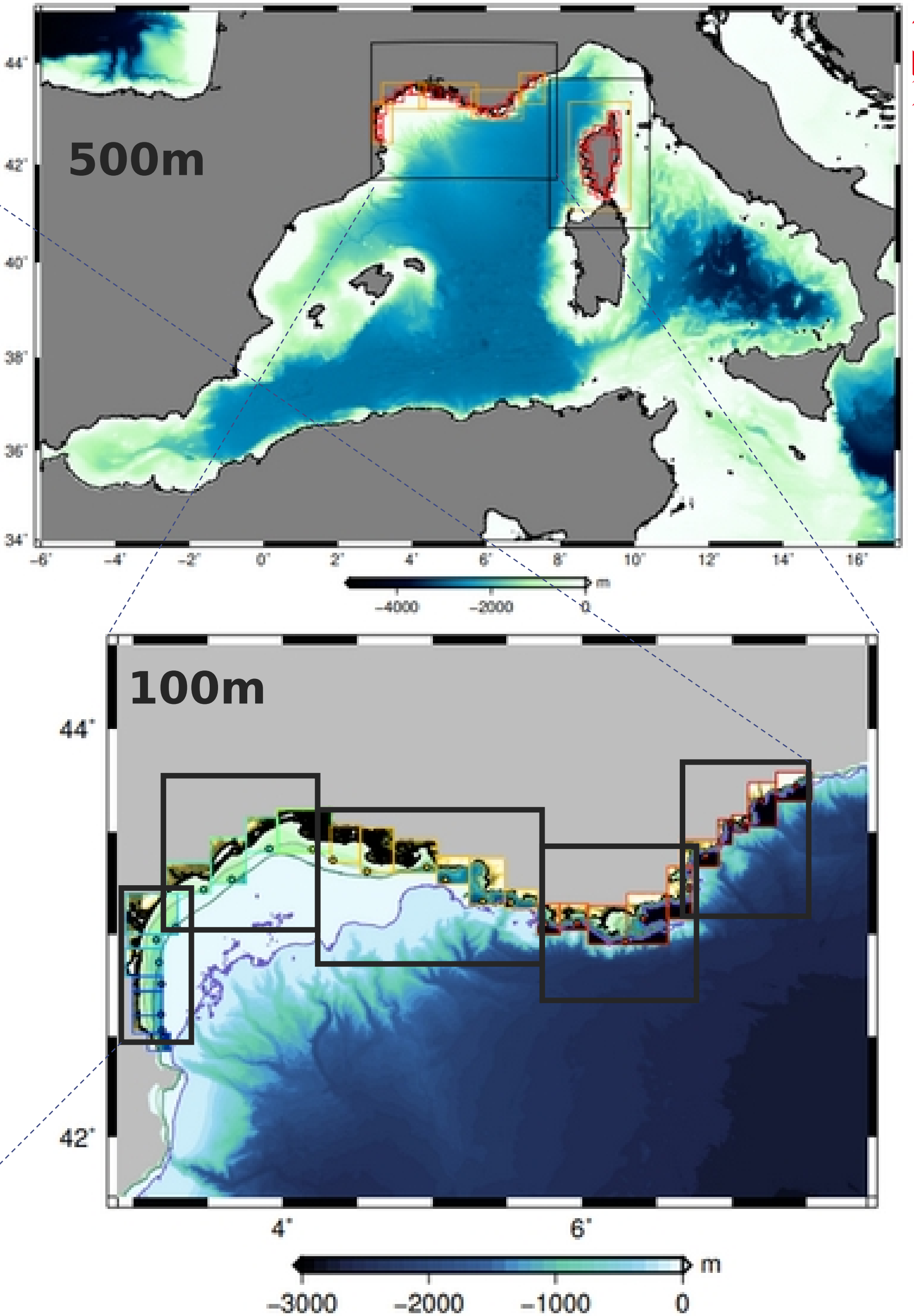


Depth (meters)	Velocity (km/h)	Wave length (km)
7000	943	282
4000	713	213
2000	504	151
200	159	48
50	79	23
10	36	10.6

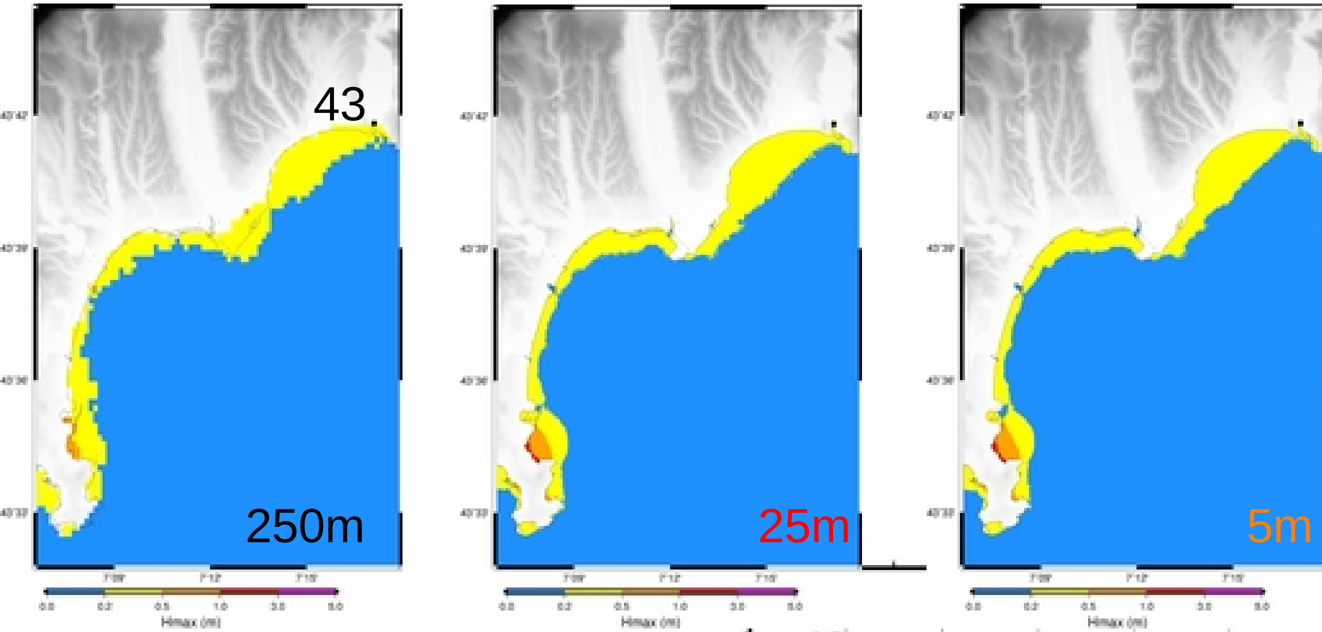
Source : UNESCO

Example of nested grids





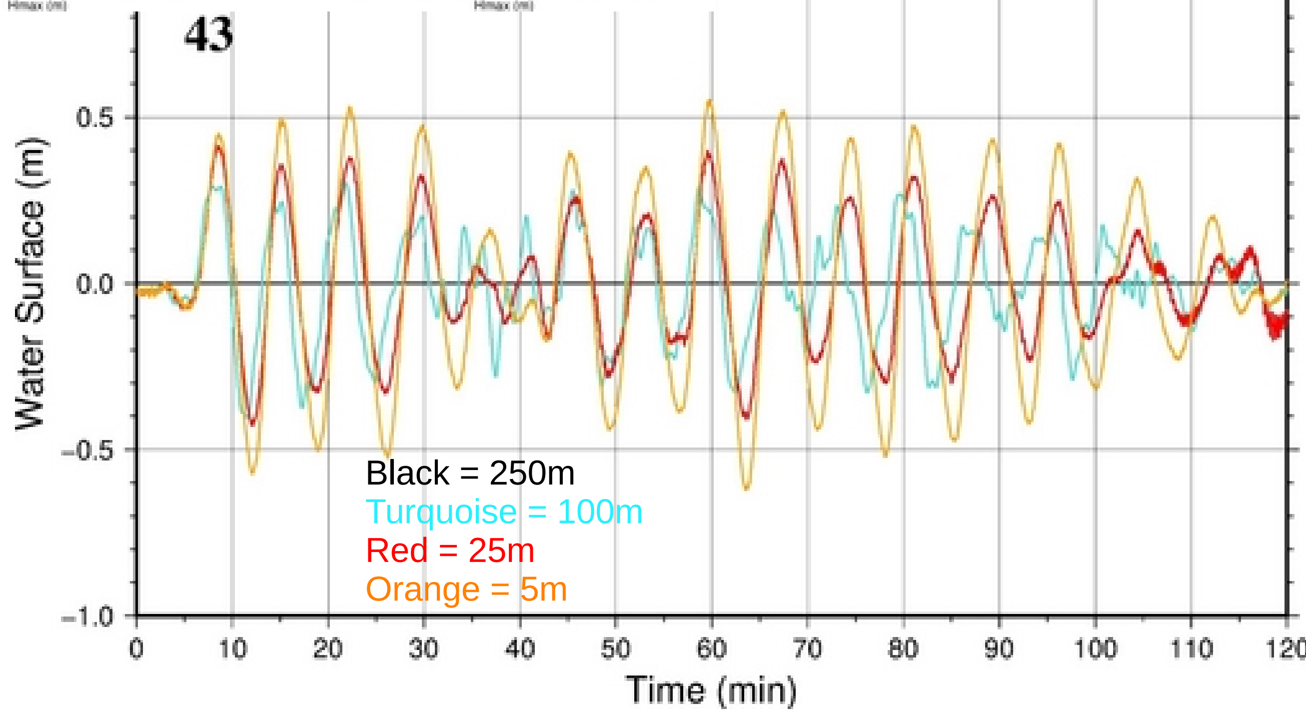
Why high resolution coastal topo-bathymetry?



Example at
Nice Harbor

Event from the
Ligurian Sea
Mw 6.9

< 30 m resolution grids required to capture coastal effects (amplifications, attenuations, resonances)



Some other codes wordwide

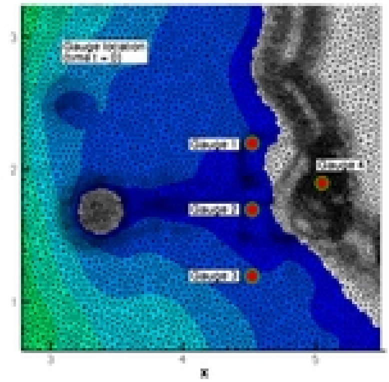
- **MOST** (NOAA; Titov and Gonzalez, 1997)
- **TSUNAMI-N2** (University of Tohuku; Imamura et al., 2006)
- **COMCOT** (Cornell University)
- **GEOCLAW** (University of Washington; Berger et al, 2011)
- **BOSZ** (University of Hawaii; Roeber et al., 2012)
- **HYSEA** (University of Malaga; Macias et al., 2021)
- **JAGURS** (Baba et al., 2015)
- **FUNWAVE** (University of Delaware; Shi et al., 2012)
- **NAMI-DANCE** (Zaytsev et al., 2019)

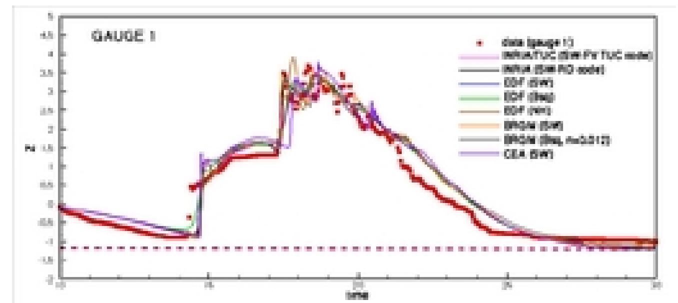
Examples of tsunami modeling
-
Benchmarks + Current and historical cases

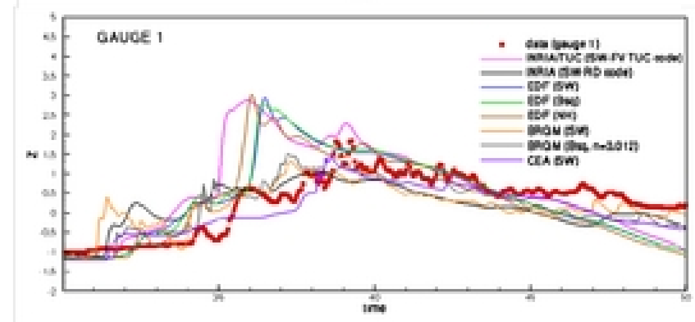
PIA TANDEM (2013-2017)

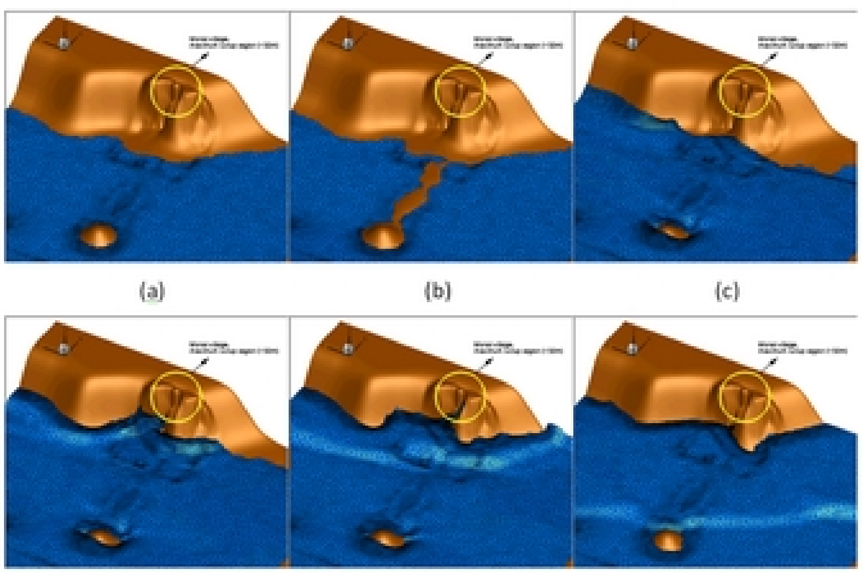
Some objectives (WP1)

- Qualification of the numerical methods to simulate tsunamis from the source to the coastline
- 19 test cases, separated into five sections:
  - Gravity generation
  - Seismic generation
  - Propagation
  - Run-up/Submersion
  - Impact
- Adaptation and coupling of modeling methods





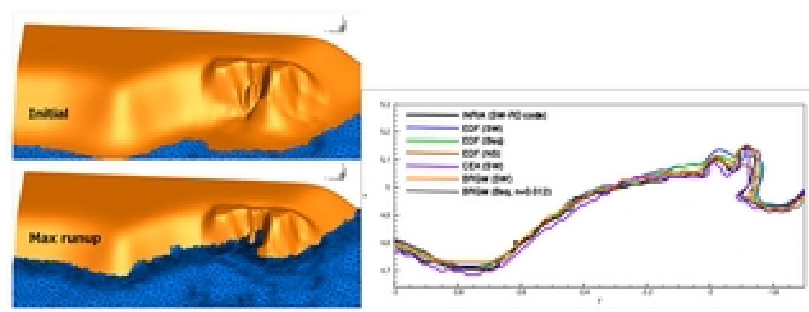




(a) (b) (c)

(d) (e) (f)

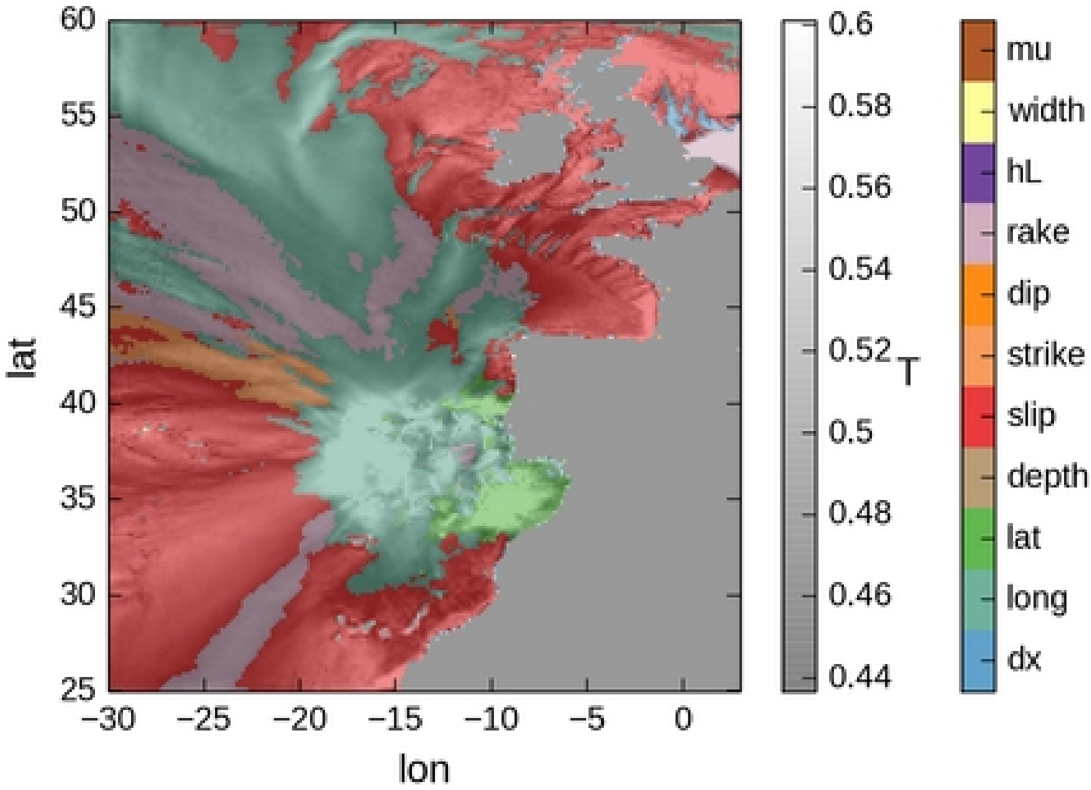
Source Inria



PIA TANDEM (2013-2017)

Some objectives (WP2)

- Sensitivity to the various parameters
- Propagation of uncertainties
- For every stage of the tsunami, from the source to the coastal processes
- For tsunamis generated by earthquakes (e.g. 1755) and landslides (Canaries)



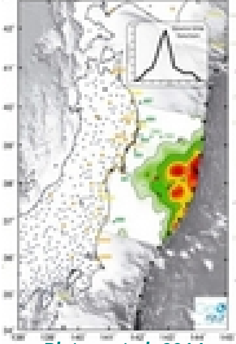
Sensitivity analysis for the 1755 event

Map of input parameters with the greatest contribution. Illumination shows the total Sobol index from the lowest (dark) to the highest (light). 6 parameters only have the greatest contribution somewhere in the map (i.e., longitude, latitude, space step, slip, strike, and rake).

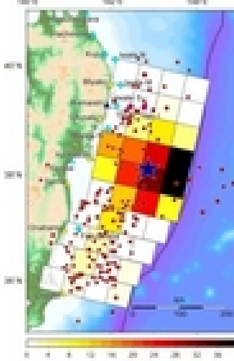
PIA TANDEM (2013-2017)

Some objectives (WP3)

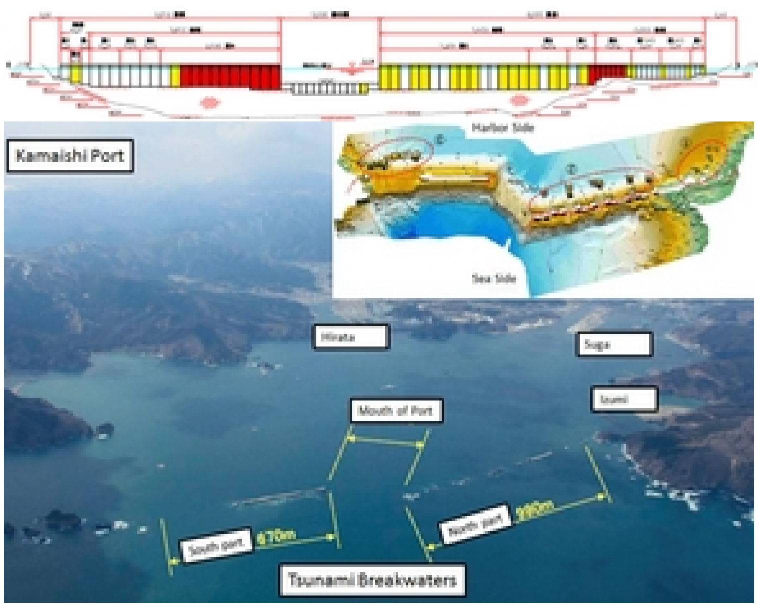
- Numerical models to be tested against the 2011 observation database, including the coastal level (Kamaishi)
- Design of protections



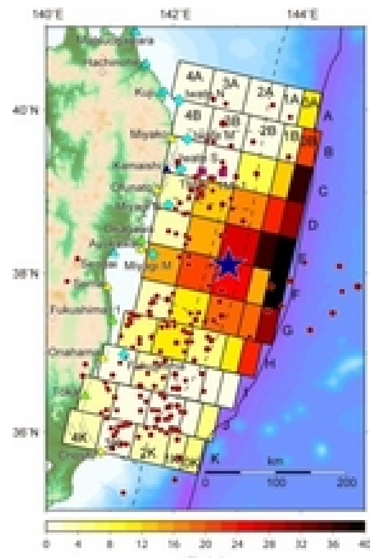
Bletery et al. 2014
Inversion of strong motion, teleseismic, onshore GPS and offshore tsunamic data



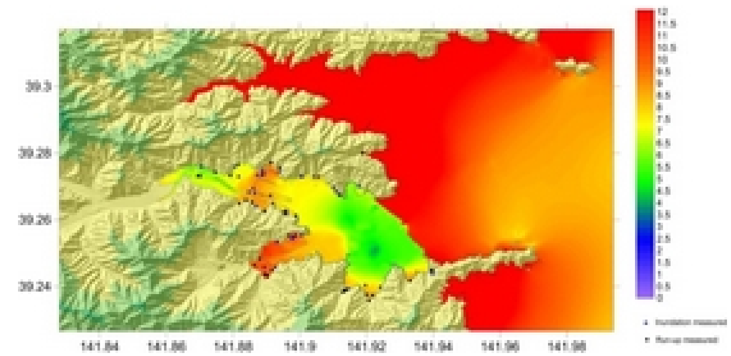
Fuji et al. 2011
Tsunami waveform inversion



(PIANC report, 2014 - Photos from Tohoku Dev. Bureau, MLIT, Japan – Arikawa et al. 2012)

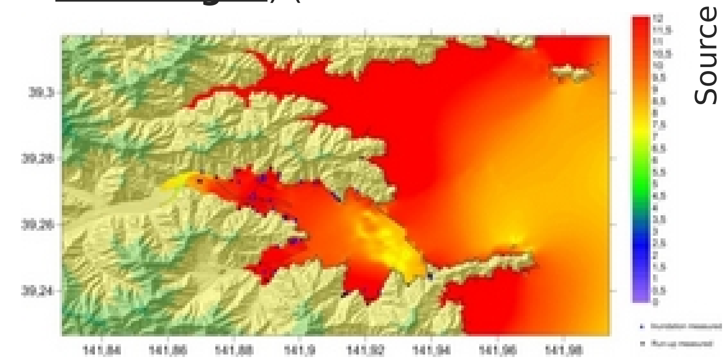


Satake et al. 2013
Tsunami waveform inversion



Maximal sea-surface elevation during the simulation **(breakwater supposed undamaged)** (source of Satake et al.

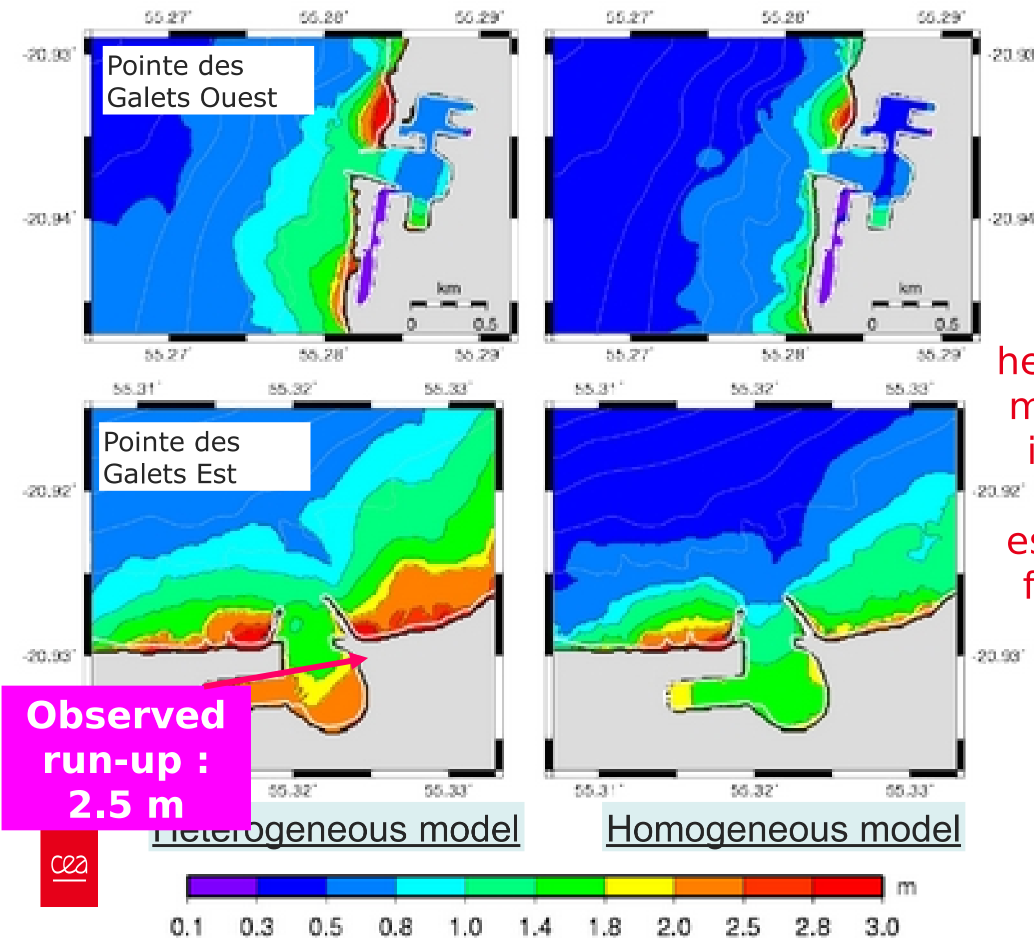
Source BRGM



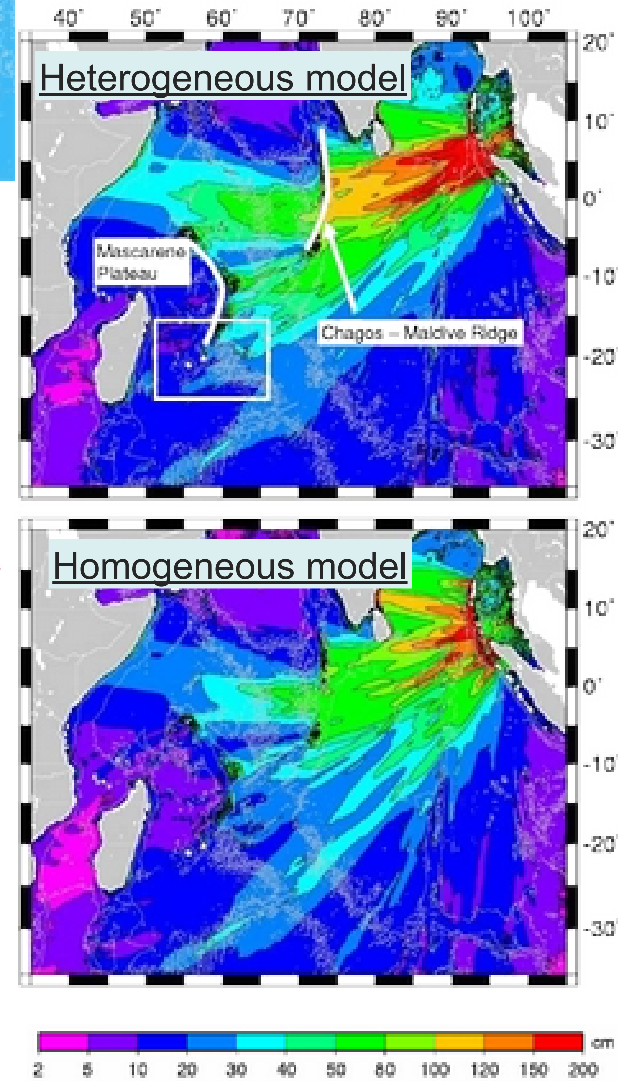
Maximal sea-surface elevation during the simulation (**breakwater damaged from the beginning of simulation**).

DEM realized on Kamaishi (source BRGM)

Sumatra 2004 - Modeling at La Réunion



Source heterogeneities must be taken into account when estimating far-field impacts



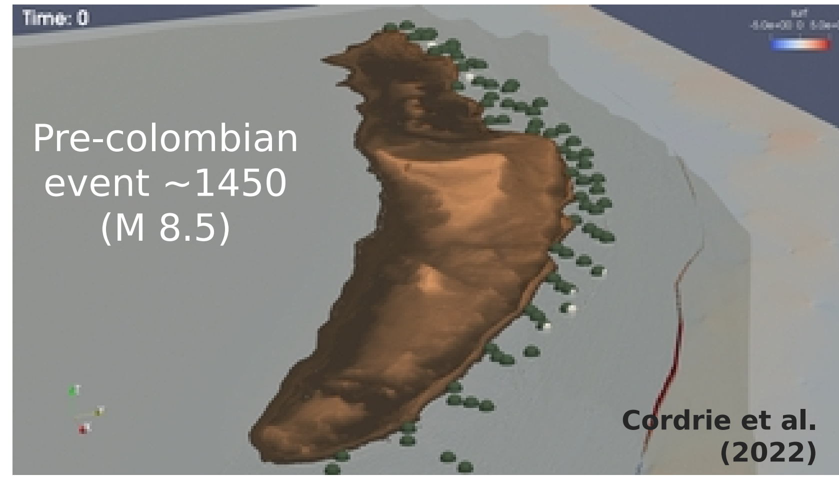
Hébert et al., BSSA, 2007

ANR CARQUAKES (2018-2023)

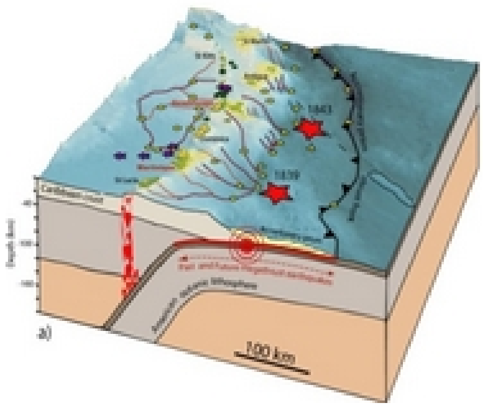
Impact of major earthquakes and tsunamis in the Lesser Antilles on coastal and deep-sea sedimentation, coral growth and human settlement (PI N. Feuillet, IPGP)

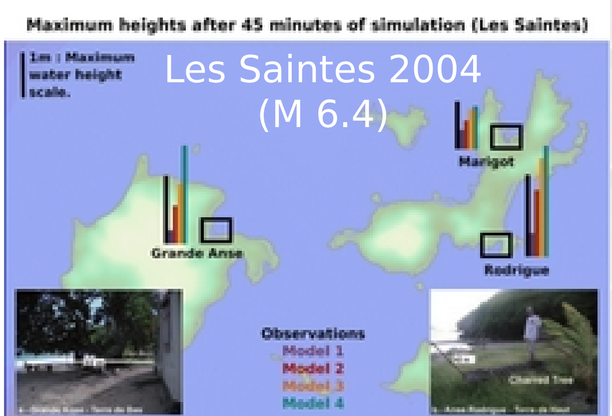
- *PhD L. Cordrie (2019-2022)*
  - Modeling of historical tsunamis in the Lesser Antilles and validation of hazard estimation methods

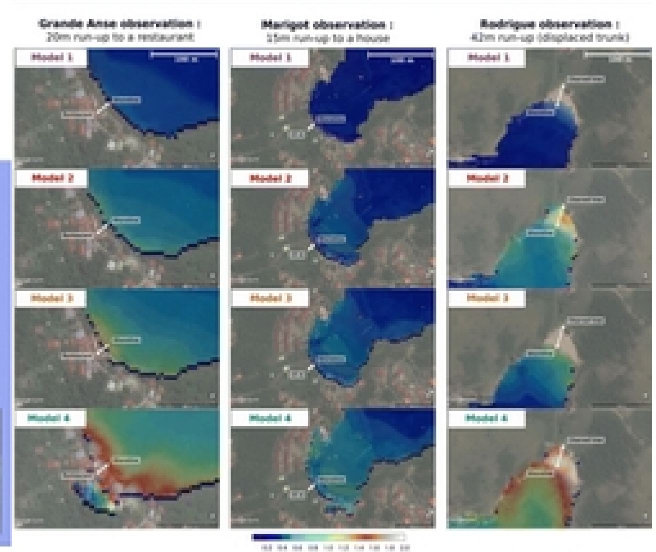
Data and pictures from: Atwater et al., 2017

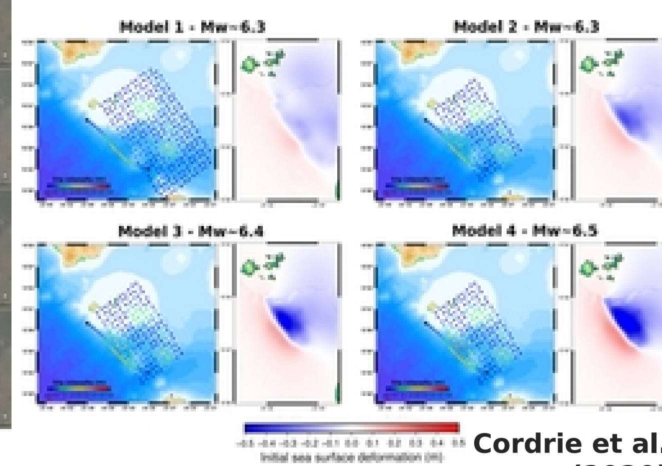


Cordrie et al. (2022)



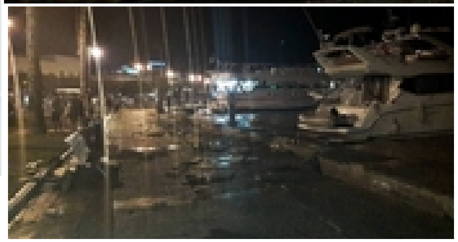


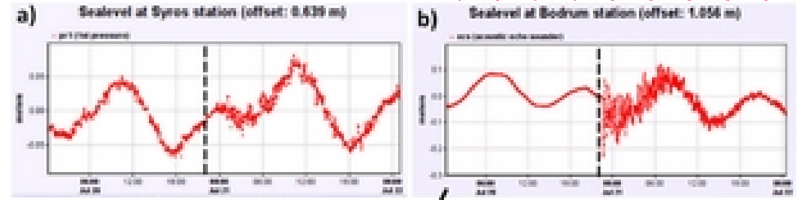


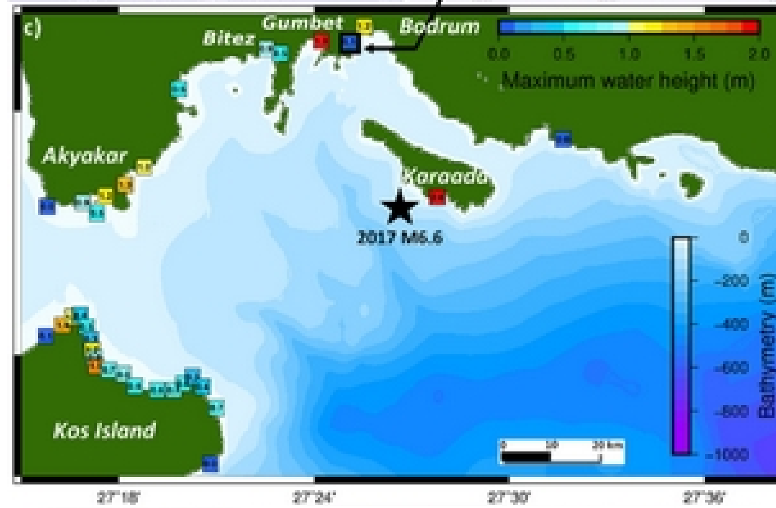


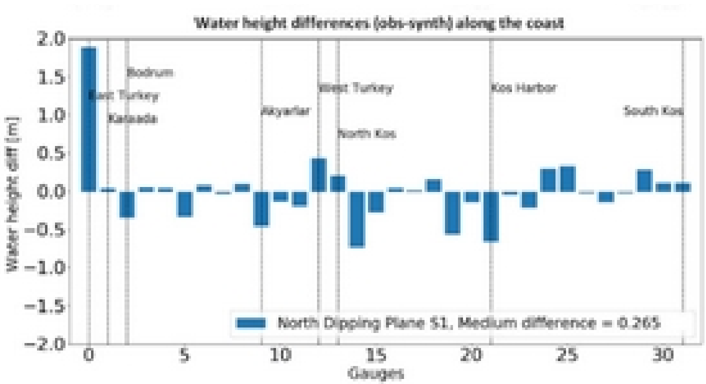
Cordrie et al. (2020)

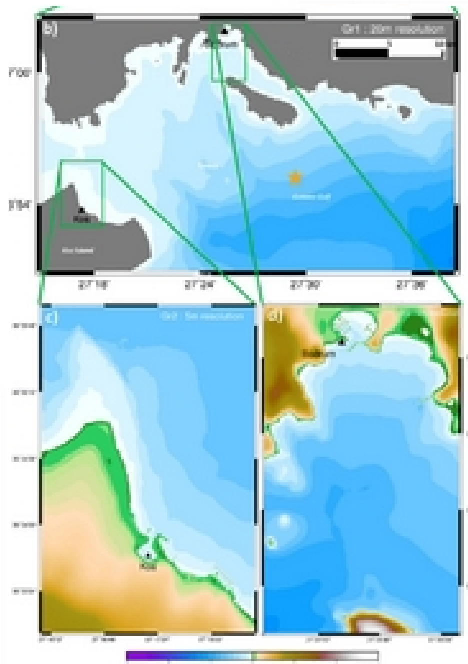
Bodrum 2017, Greece-Turkey (M 6.6)



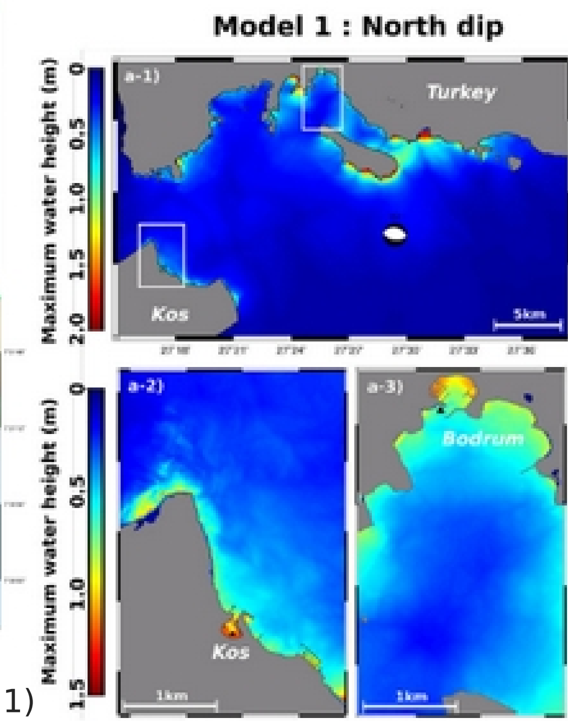




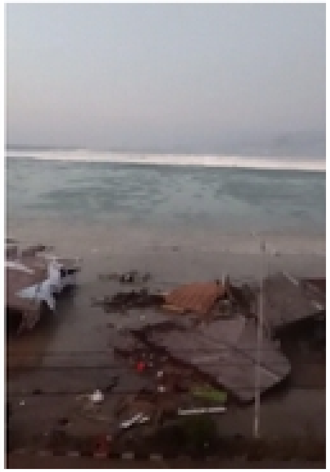


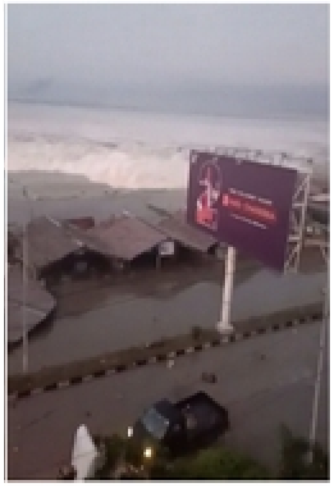


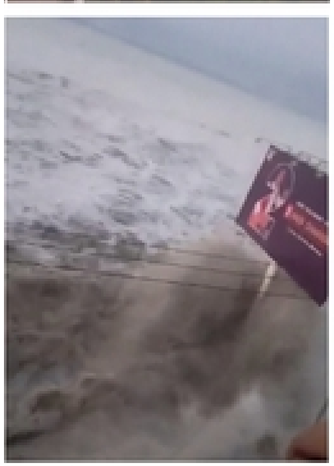
Cordrie et al. (2021)

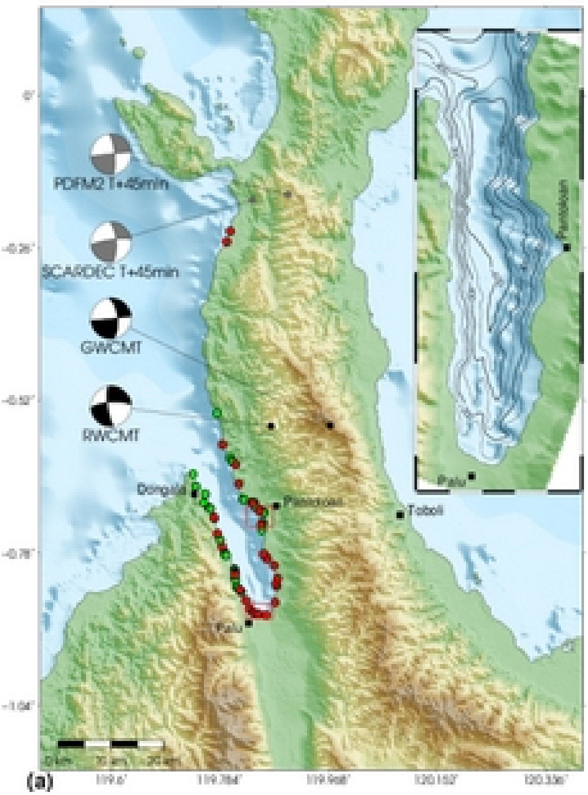


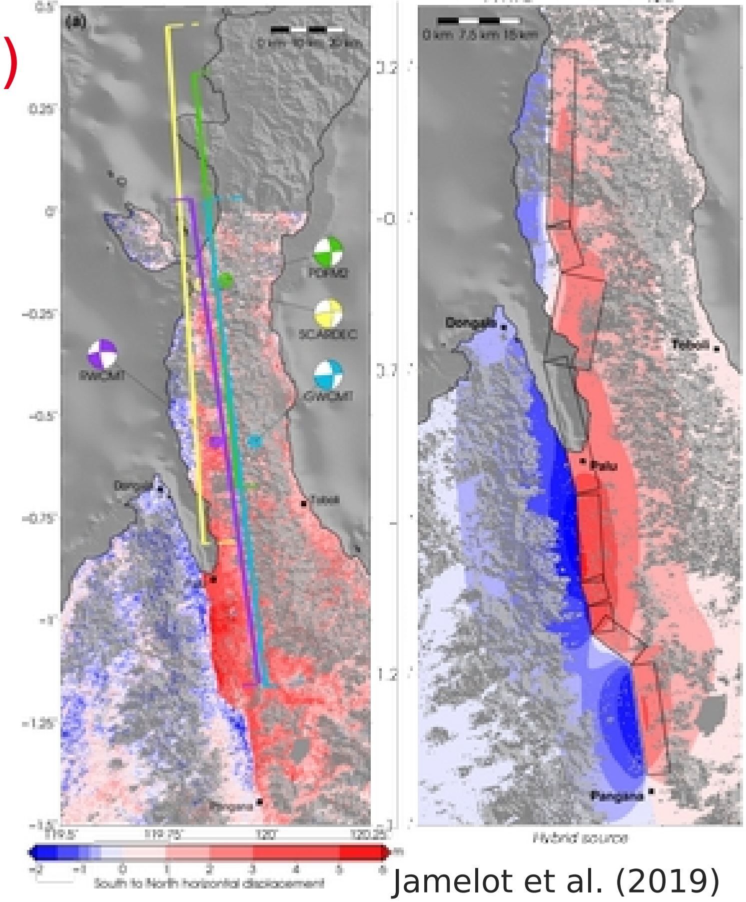
Palu 2018, Sulawesi (M 7.1)



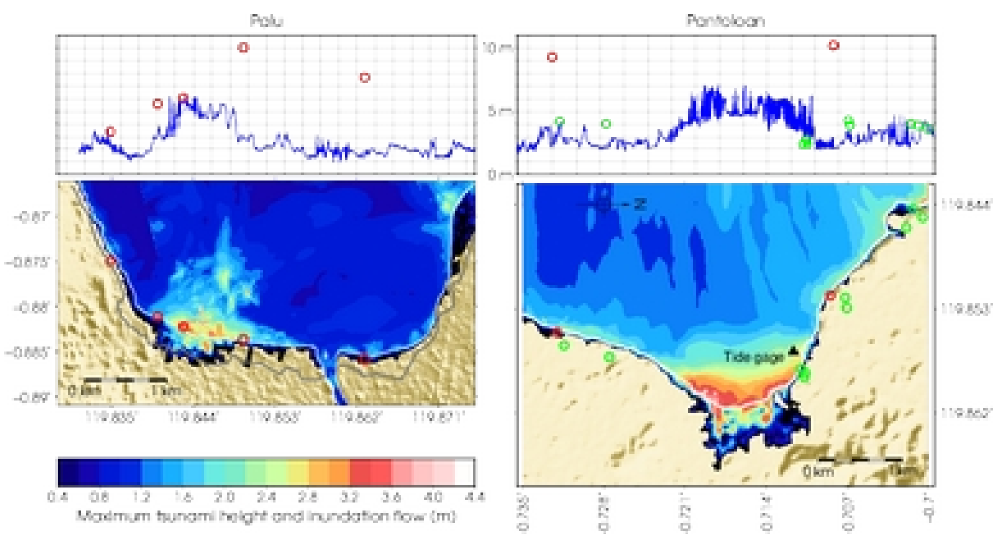








Jamelot et al. (2019)

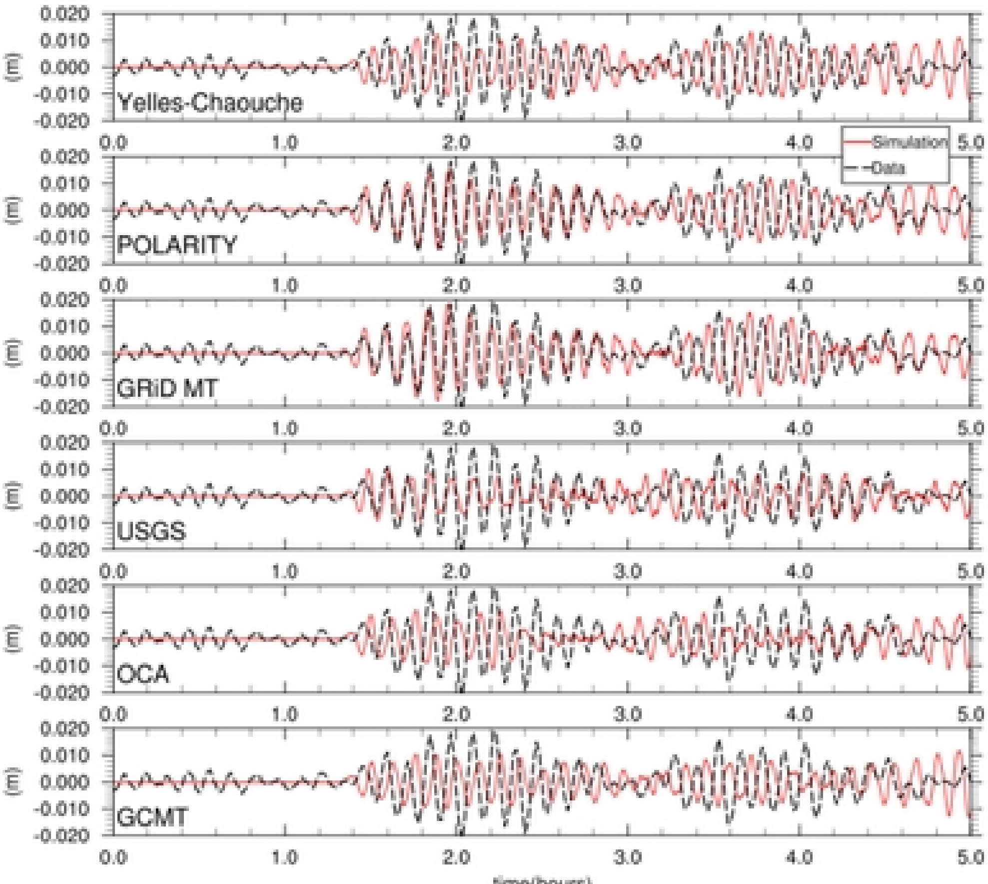


Bejaia - Algeria 2021 (M 6.0) : dispersive propagation

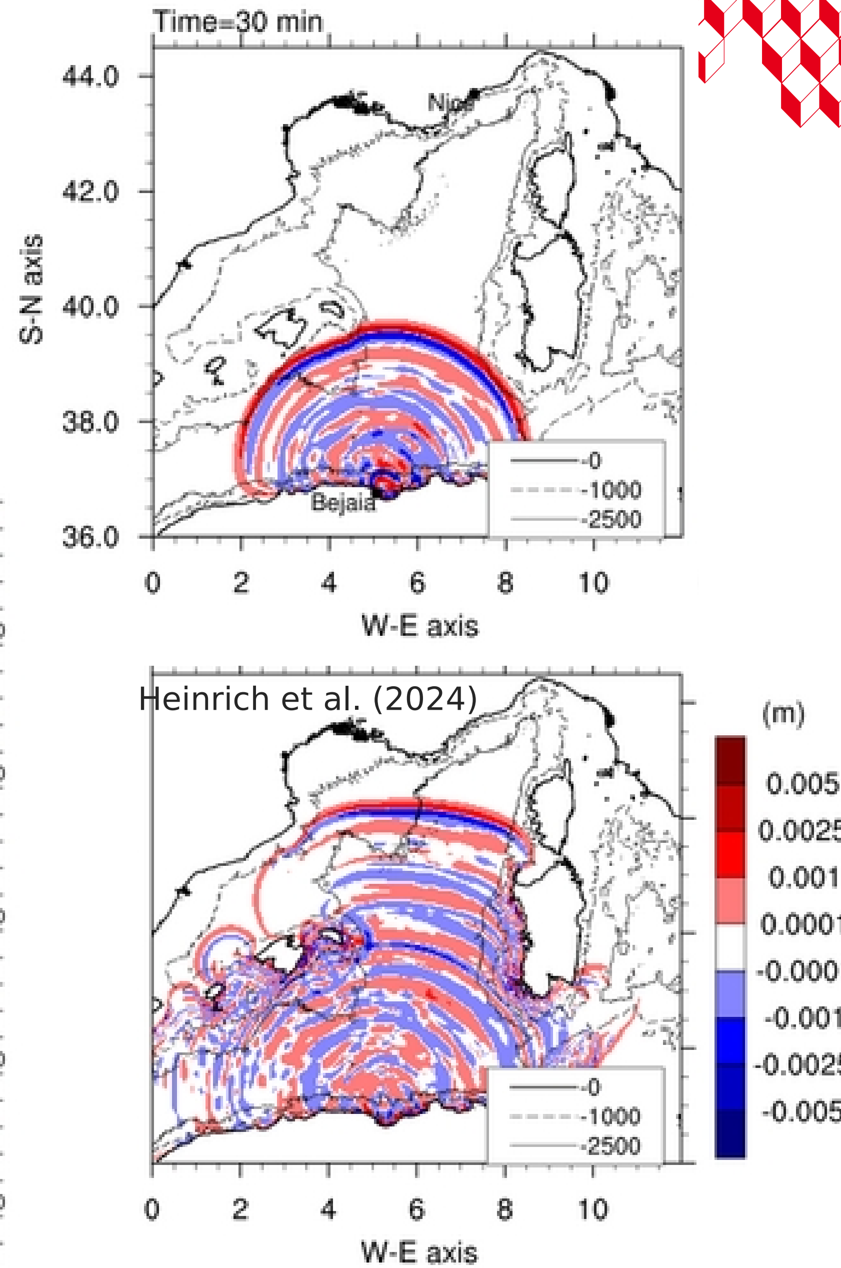
Simulation of the Mediterranean tsunami generated by the M_w 6.0 event offshore Bejaia (Algeria) on 18 March 2021

P Heinrich, A Dupont, M Menager, A Trilla, A Gailler, B Delouis, H Hébert

Geophysical Journal International, Volume 237, Issue 3, June 2024, Pages 1400–1413,
https://doi.org/10.1093/gji/ggae121

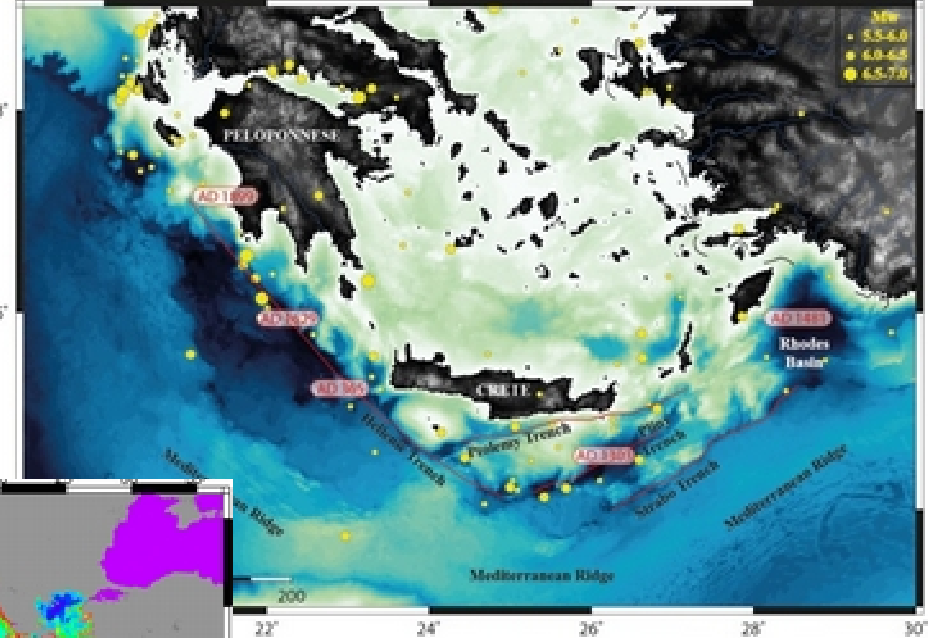


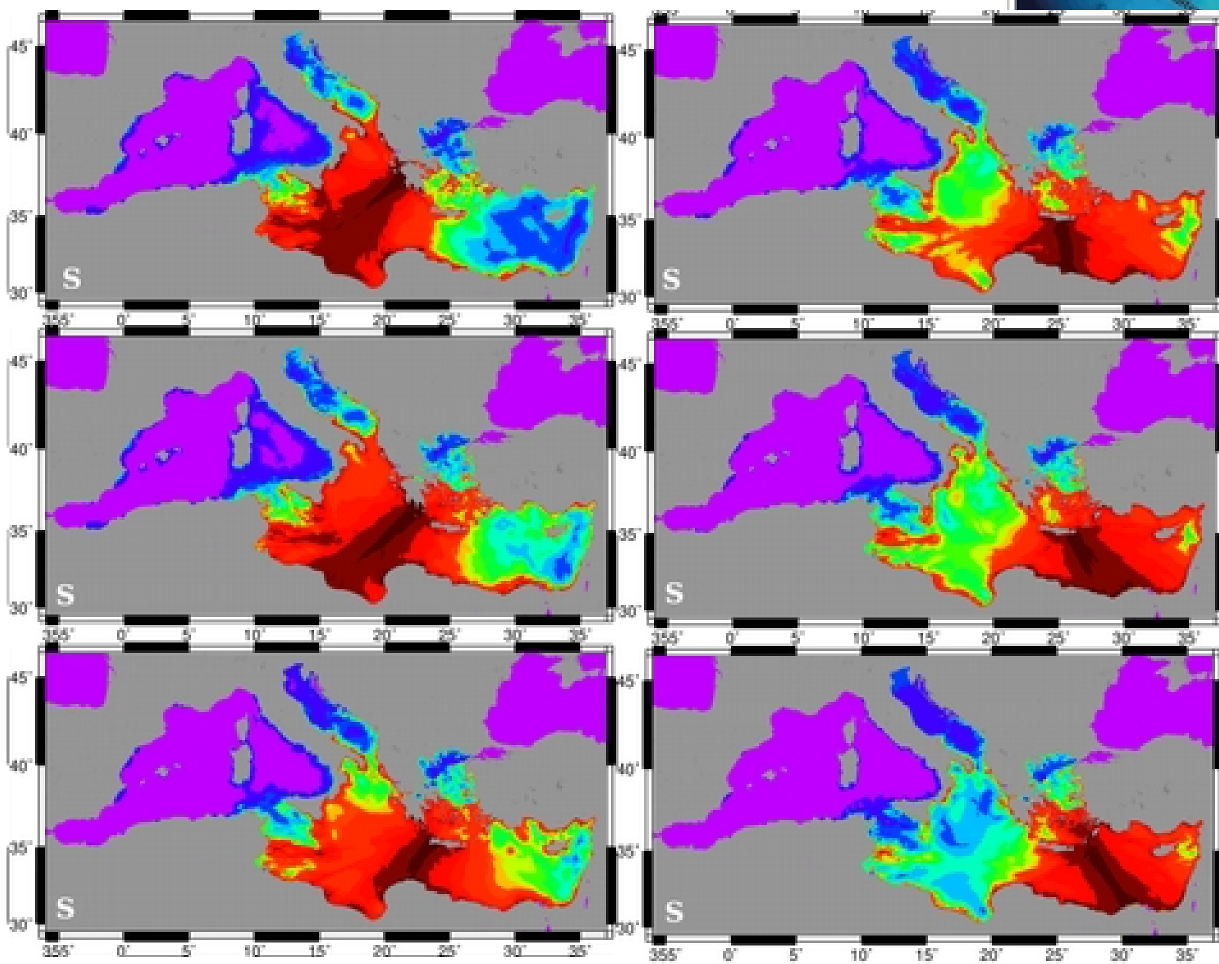
Time series computed at Nice tide-gage



Heinrich et al. (2024)

Earthquake in the eastern Mediterranean:
What's the risk for the French coast?





The tsunami risk along the French coast exists for earthquakes of M ≥ 8.0 generated along the Hellenic arc.

-> maximum tsunami wave heights modelled in Corsica: 5 to 40-50 cm (depending on magnitude and source configuration)

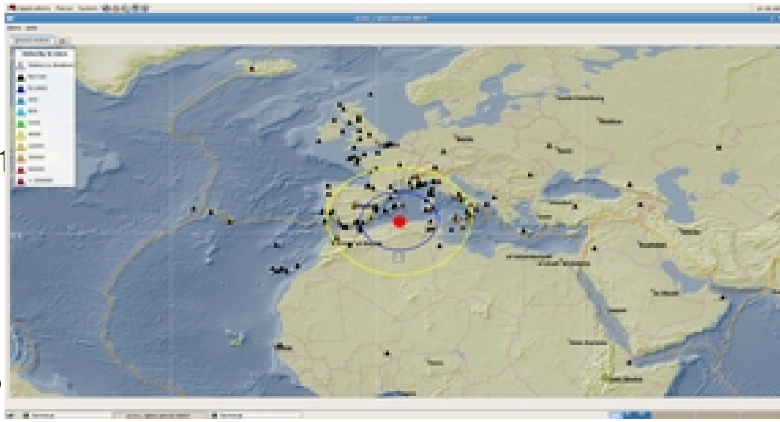
Gailler et al. (2015)

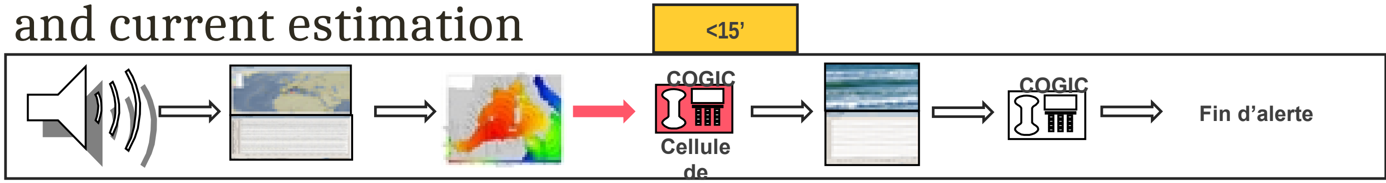
Challenge of tsunami forecasting in near-field operational context

Predicting coastal flooding in real time: a major challenge in near field context

- Current functioning of warning systems
  - Focused on the first parameters of the earthquake
    - 24-hour seismic monitoring
    - Seismic data processing (M, location)
  - Basin-wide tsunami hazard modelling
    - At CENALT: Cassiopée (pre-calculated database), Taitoko (real-time simulation)
    - The coastal water height is not calculated
  - Full computation up to coastal impact incompatible with real time near field or regional forecasting.
    - Non-linear model
    - High resolution bathymetric / topographic dat
    - Considerable computation time : > 45 min
- Challenge
  - Rapid determination of coastline amplitudes
  - Real-time run-up and current estimation

!
15 min
to issue the 1st message to the civil authorities





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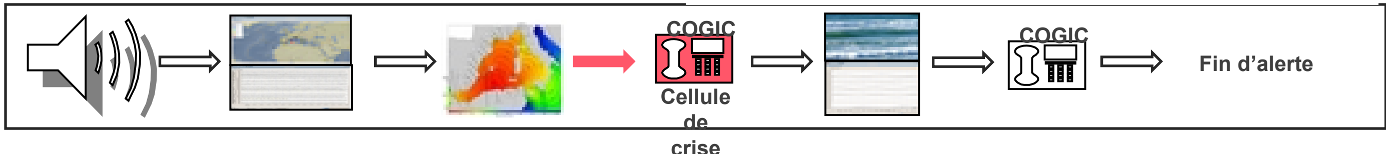
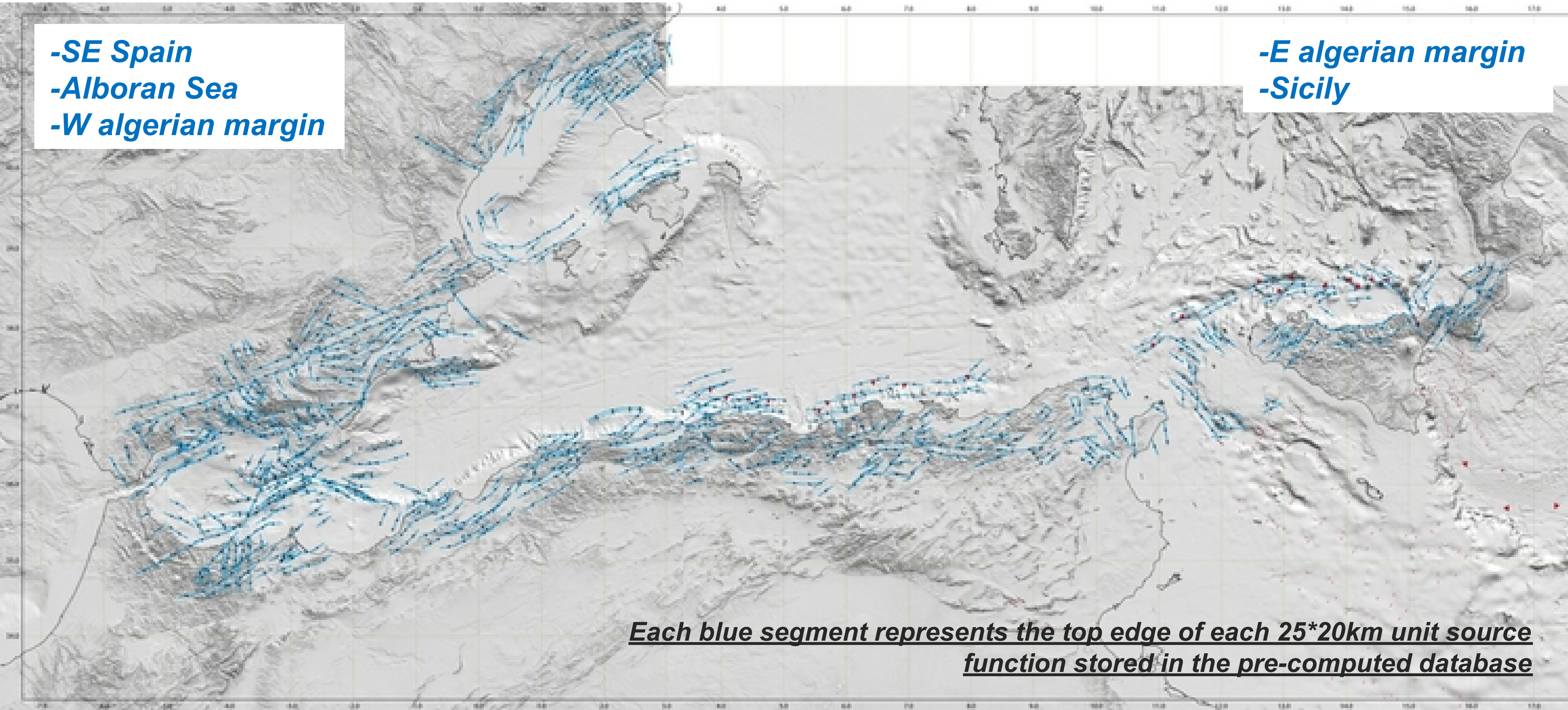


How does the Model-based tsunami prediction system work?

Pre-computed database for the Mediterranean Basin

Discretization of the main seismogenic faults bounding the basin in equal segments of 25km length whose centers correspond to the source locations.

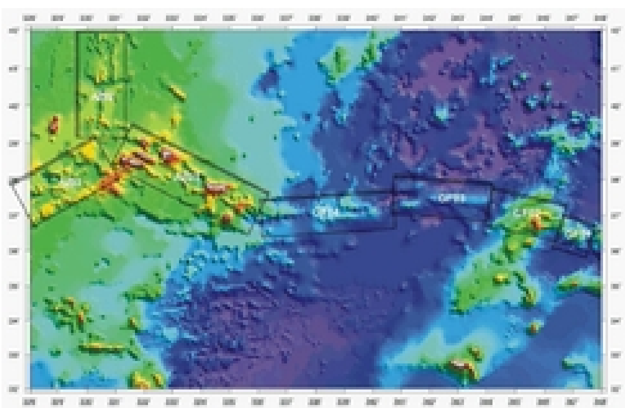
The scenario database has 1 earthquake magnitude of *Mw* = 6.76 (M_0=1.75E+19 N.m) at each source location, with a fixed rectangular rupture area of 25 km by 20 km in size and 1 m in slip.

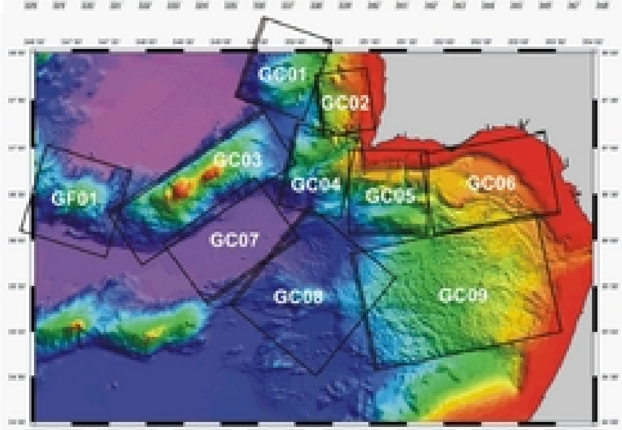


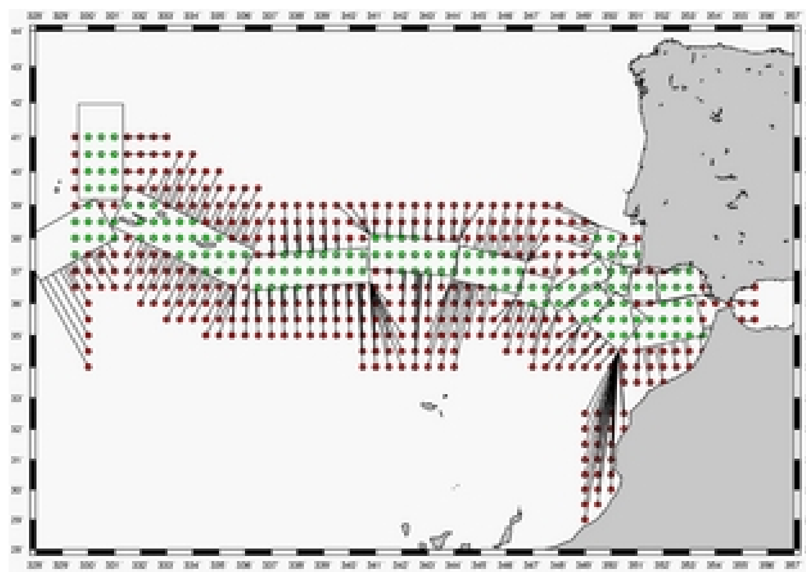
Pre-computed database for the NE Atlantic Basin

Division of the Azores-Gibraltar transform zone in several boxes in which all sources have the same fault parameters (strike, dip, rake), derived from historical focal mechanisms that would induce the worst tsunami scenarios.

The scenario database has 5 earthquake magnitudes of *Mw* = 6.5, 7.0, 7.5, 8.0, and 8.5 at each source location.
The rupture area parameters (L, W, slip) are fixed for each magnitude, derived from empirical relationships.







Each dot represents the center of a source location for which 5 earthquake magnitudes scenarios are stored in the pre-computed database

Geographical location of tsunami sources and fault parameters regionalization done by the Joint Research Centre for Tsunami Assessment Modeling System (Annunziato, 2007) in Portugal.

Scenarios calculation strategy

•**Source parameters of the scenarios stored in the pre-computed database**

MEDITERRANEAN

L (km)	W (km)	surface (km2)	slip (m)	R = 35E+09	
				Mo (N.m)	Mw(calculated)
25	20	500	1	1.75E+19	6.76

- **1 earthquake magnitude of *Mw* = 6.76 at each source location**

ATLANTIC

Mw(reference)	L (km)	W (km)	surface (km2)	slip (m)	R = 45E+09	
					Mo (N.m)	Mw(calculated)
6,5	20	10	200	0,8	7,20E+18	6,50
7	50	20	1000	1	4,50E+19	7,04
7,5	100	35	3500	1,4	2,21E+20	7,50
8	200	45	9000	3,5	1,42E+21	8,03
8,5	370	55	20350	7,8	7,14E+21	8,50

- **5 earthquake magnitudes of *Mw* = 6.5, 7.0, 7.5, 8.0, and 8.5 at each source location**

•**Scaling factor Fs (multiplier) derived from linearity of physics of tsunami generation and propagation in deep ocean**

$M_{w(comp)}$	Nb of unit sources involved (25*20 km)	F_s
6.3	1	0.20
6.4	1	0.29
6.5	1	0.40
6.6	1	0.57
6.7	1	0.81
6.8	1	1.14
6.8	2	0.57
6.9	1	1.61
6.9	2	0.81
7.0	2	1.14
7.1	2	1.61
7.2	2	2.27
7.2	3	1.51
7.3	3	2.14
7.3	2*4	0.80
7.4	3	3.02
7.4	2*4	1.13
7.5	2*4	1.60
7.6	2*4	2.26
7.6	2*5	1.81
7.7	2*4	3.19
7.7	2*5	2.55
7.8	2*5	3.61
7.8	2*6	3.00
7.9	2*6	4.24
7.9	2*7	3.64
8.0	2*8	4.50

Mw(comp)	Mw(ref)	Fs
6,3	6,5	0,50
6,4	6,5	0,71
6,5	**6,5**	**1,00**
6,6	6,5	1,41
6,7	6,5	2,00
6,8	7	0,50
6,9	7	0,71
7	**7**	**1,00**
7,1	7	1,41
7,2	7	2,00
7,3	7,5	0,50
7,4	7,5	0,71
7,5	**7,5**	**1,00**
7,6	7,5	1,41
7,7	7,5	2,00
7,8	8	0,50
7,9	8	0,71
8	**8**	**1,00**
8,1	8	1,41
8,2	8	2,00
8,3	8,5	0,50
8,4	8,5	0,71
8,5	**8,5**	**1,00**
8,6	8,5	1,41
8,7	8,5	2,00
8,8	8,5	2,82
8,9	8,5	3,98

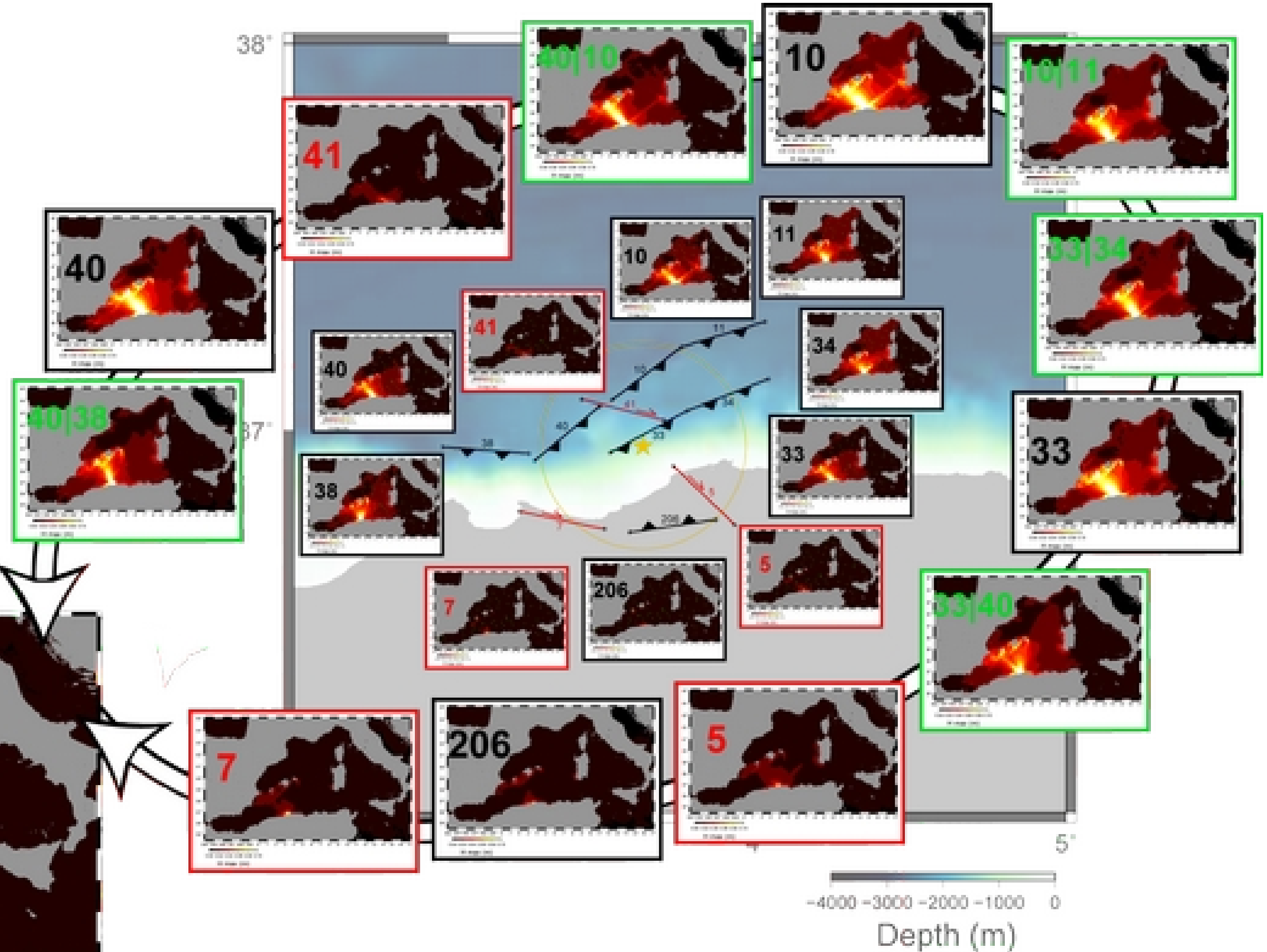
Scenario calculation strategy

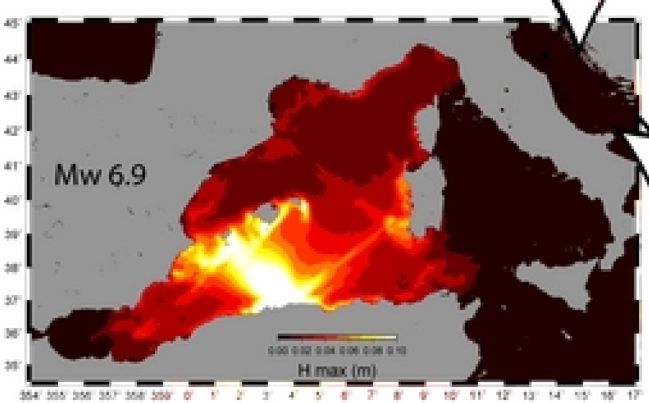
***Hmax:** maximum wave height after 3h of propagation*

(3) <u>Final composite Hmax:</u>

Max (40-41-10-33-5-206-7-40|38-40|10-10|11-33|34-33|40)

=> Mw=6.9, taking into account the uncertainty on Magnitude

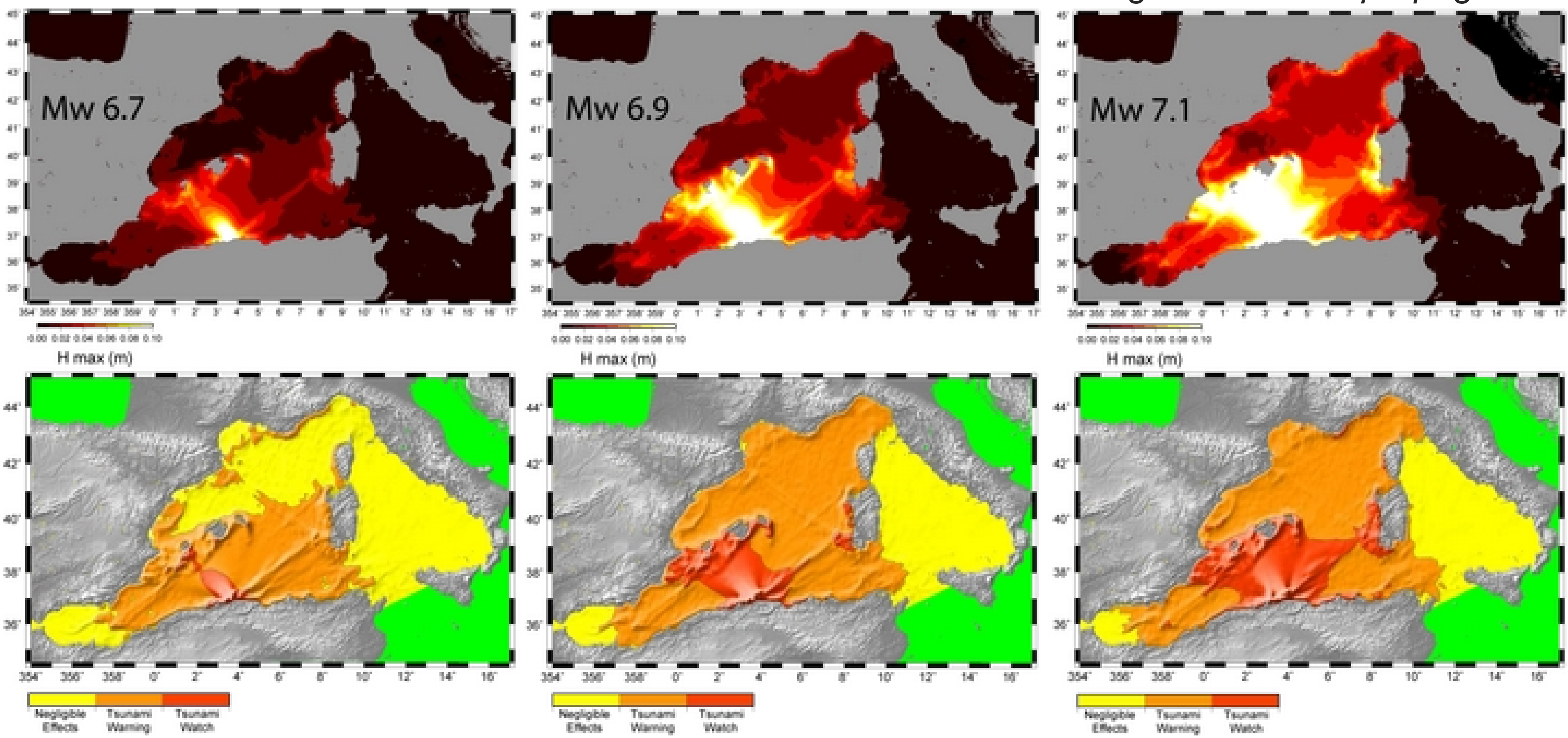




Final composite Hmax composites obtained from the different agregation solutions, for:

-Mw 6.9 +/- 0.2 **-Depth 0km (top edge)**

***Hmax:** maximum wave height after 3h of propagation*

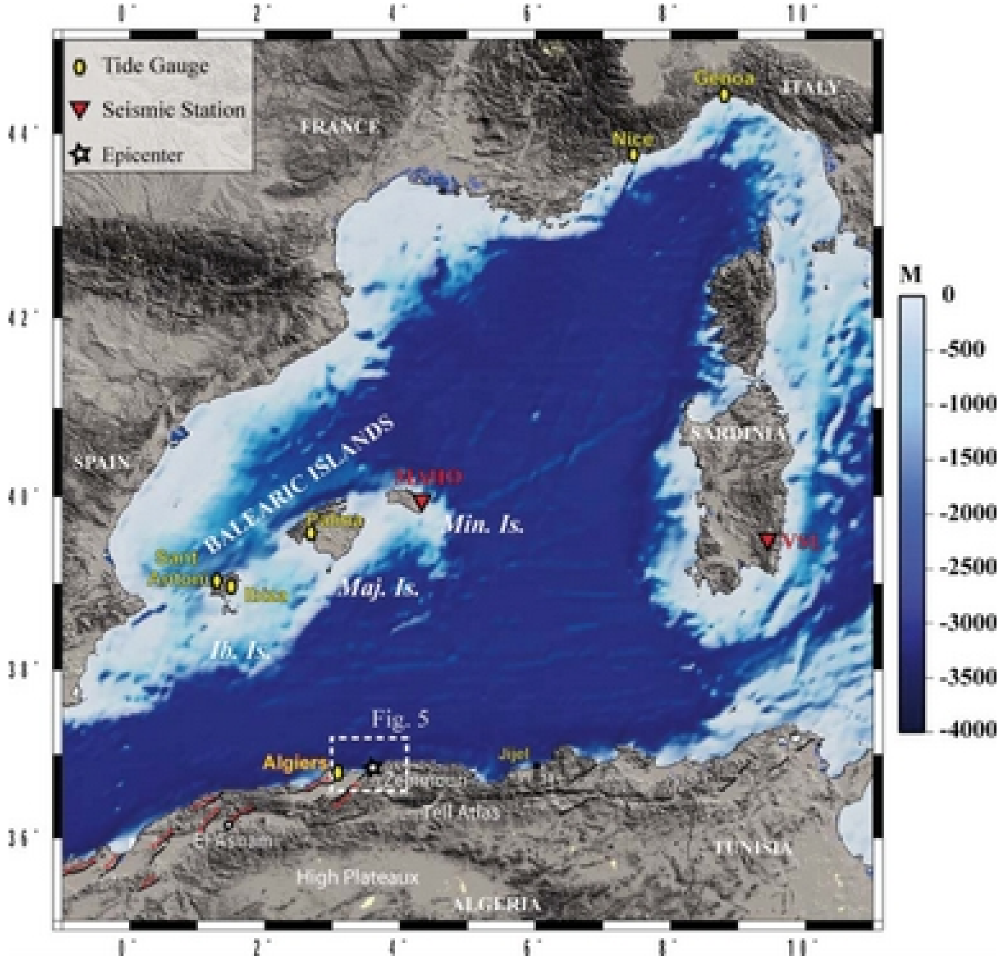


Example of Model-based tsunami prediction system results on historical events

Comparison with « on the fly » (real time) computing

Example 1 : the 2003 Boumerdès earthquake (Algeria, Mw=6.9)

Date: May 2003
Location: offshore, along the Algerian margin, close to Algiers.
Damages: 2000 casualties in the epicentral region, important damage in several Balearic harbors, significant eddies in several small pleasure harbors in southern France.

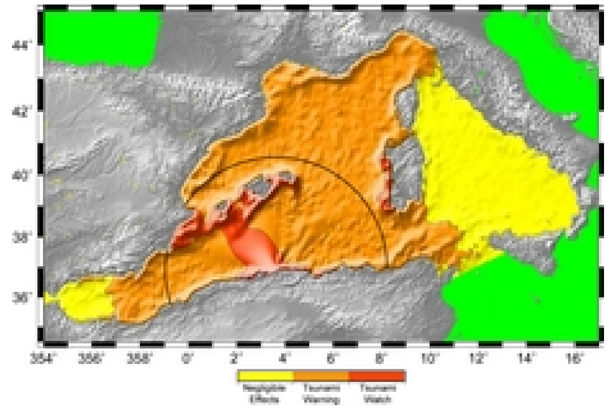


Tide-gage measurements: amplitudes from 0.5m (Palma) to 1.5m (Sant Antoni) in the Balearic, from 10cm to 60cm in southern France

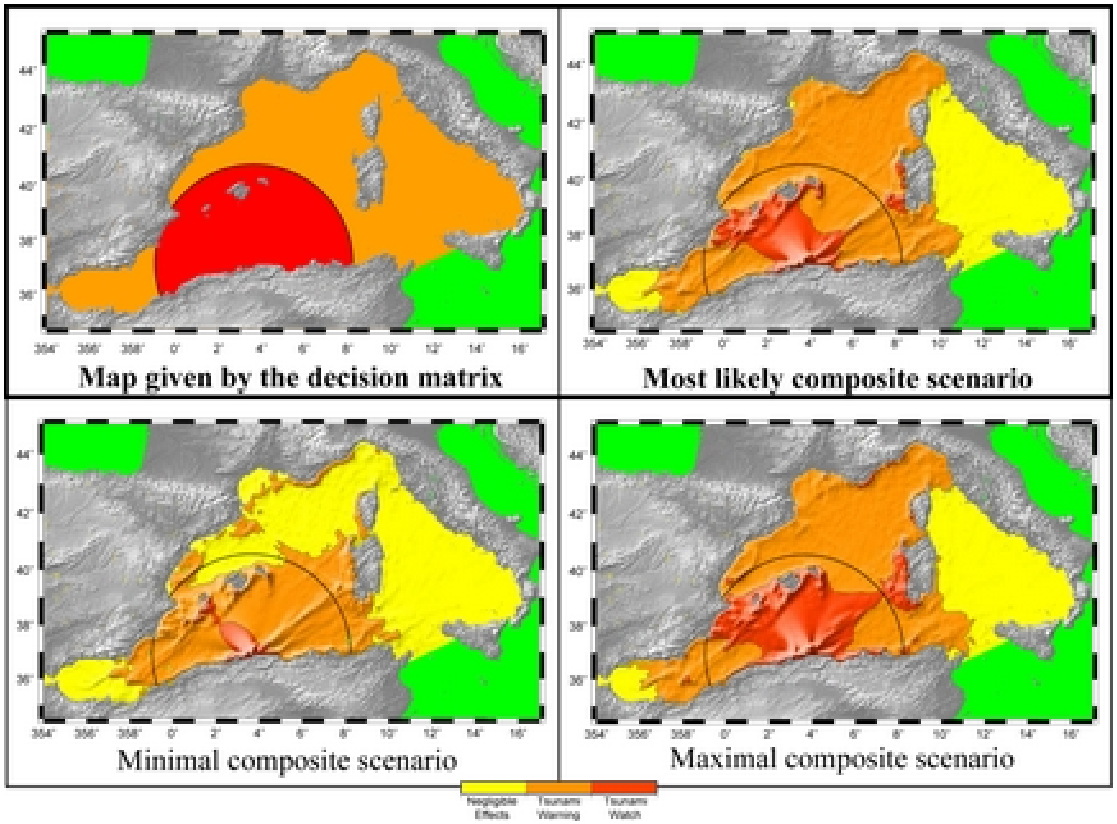
Epicenter location of the 2003 Boumerdès earthquake

Figure from Alasset et al. (2006)

Example 1 : the 2003 Boumerdès earthquake (Algeria, Mw=6.9)



Warning map resulting from « on the fly » tsunami modeling using the source parameters of Yelles et al. (2004)

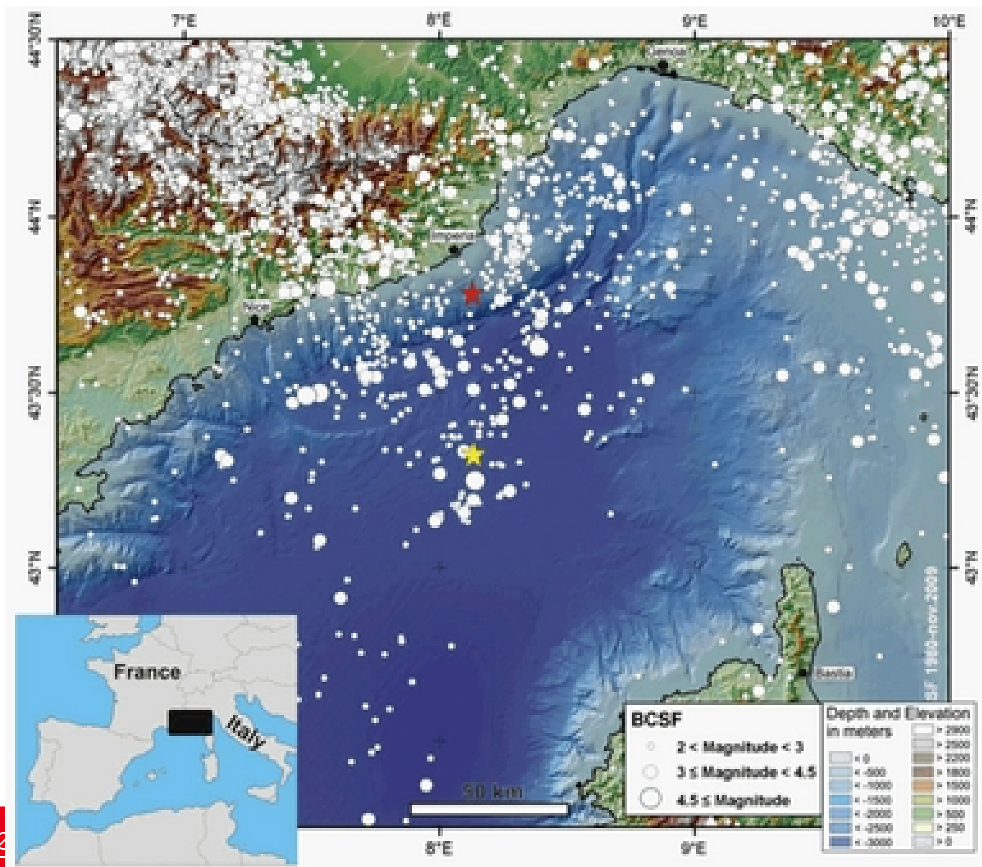


Model-based tsunami prediction system

Example 2 : the 1887 Imperia earthquake (Ligurian Sea, Mw=6.5)

Date: February 1887
Location: offshore, in the Ligurian Sea, close to the Italian coast.
Damages: intensity of X (MSK), death of 600 persons on the Italian coast, a few casualties on the French coast between Menton and Nice.

=> Strongest historical earthquake in this area



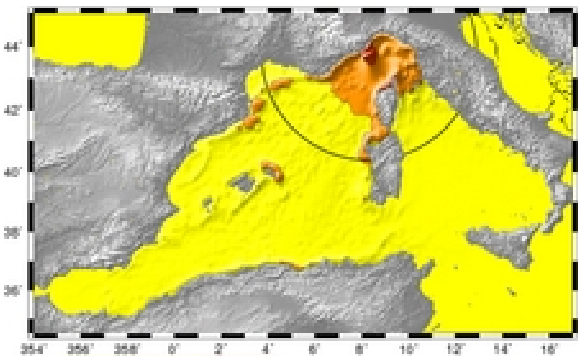
Approximate epicenter location of the 2 major historical earthquakes in the area:

[red star] Feb. 23, 1887; Mw~6.5-6.7

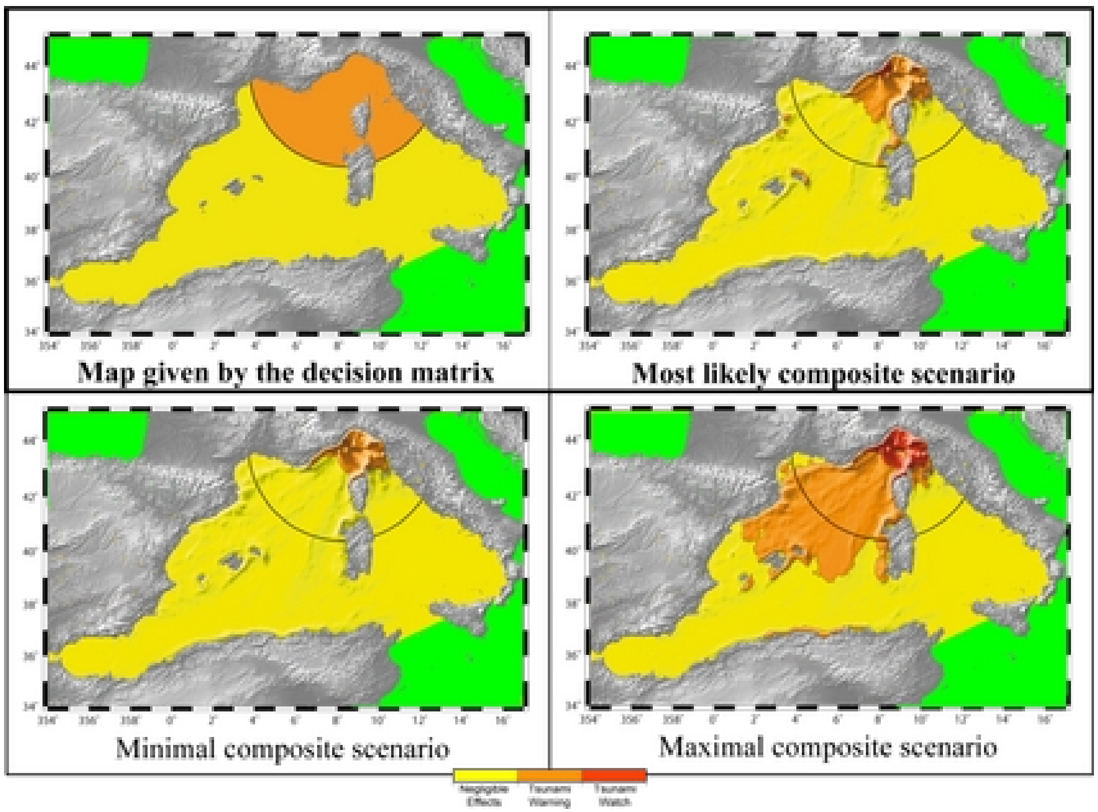
[yellow star] July 19, 1963; Ml=6.0

Figure from Larroque et al. (2011)

Example 2 : the 1887 Imperia earthquake (Ligurian Sea, Mw=6.5)



Warning map resulting from « on the fly » tsunami modeling using the source parameters of Eva et al. (2006)

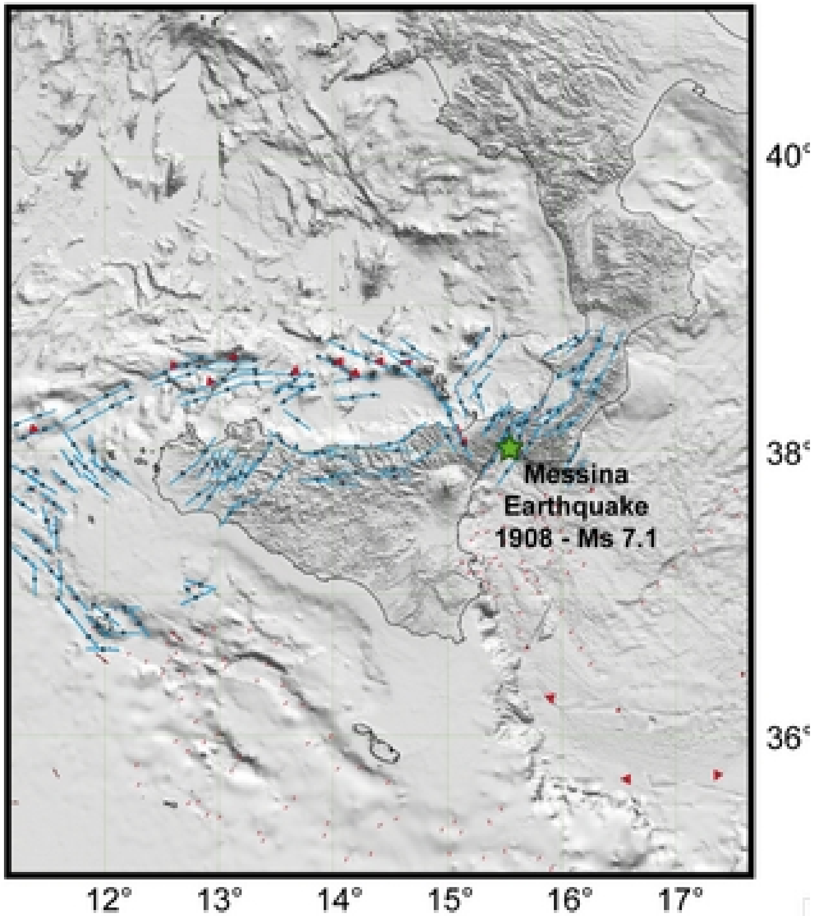


Model-based tsunami prediction system

Example 3 : the 1908 MESSINA earthquake (Sicily, M_s=7.1)

Date: 1908
Location: Messina Straits (Sicily-Calabria area).

Damages: largest event that hit the Italian coasts during the last century. 60000 people killed, extensive damage produced in Sicily and Calabria.

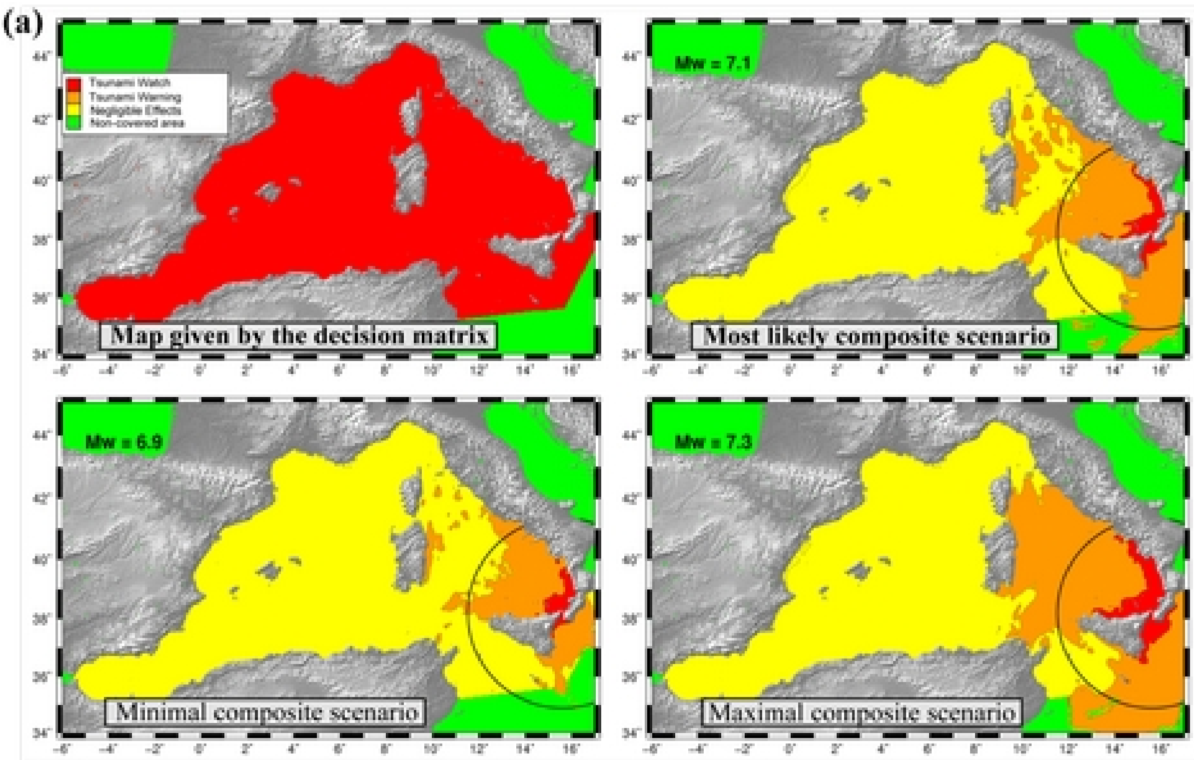


Tsunami with a large withdrawal along the whole Messina Straits. Flooding of the coast in some villages with maximum run-up up to 12m. Water waves entered 200m inland locally.

Approximate epicenter location of the major historical earthquakes in the area (green star)

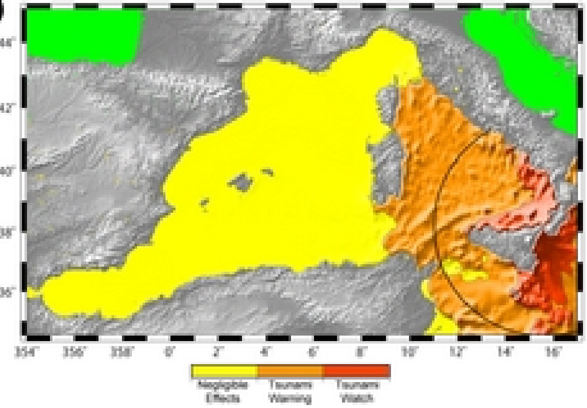
Example 3 : the 1908 MESSINA earthquake (Sicily, M_s=7.1)

(a)



Model-based tsunami prediction system

(b)

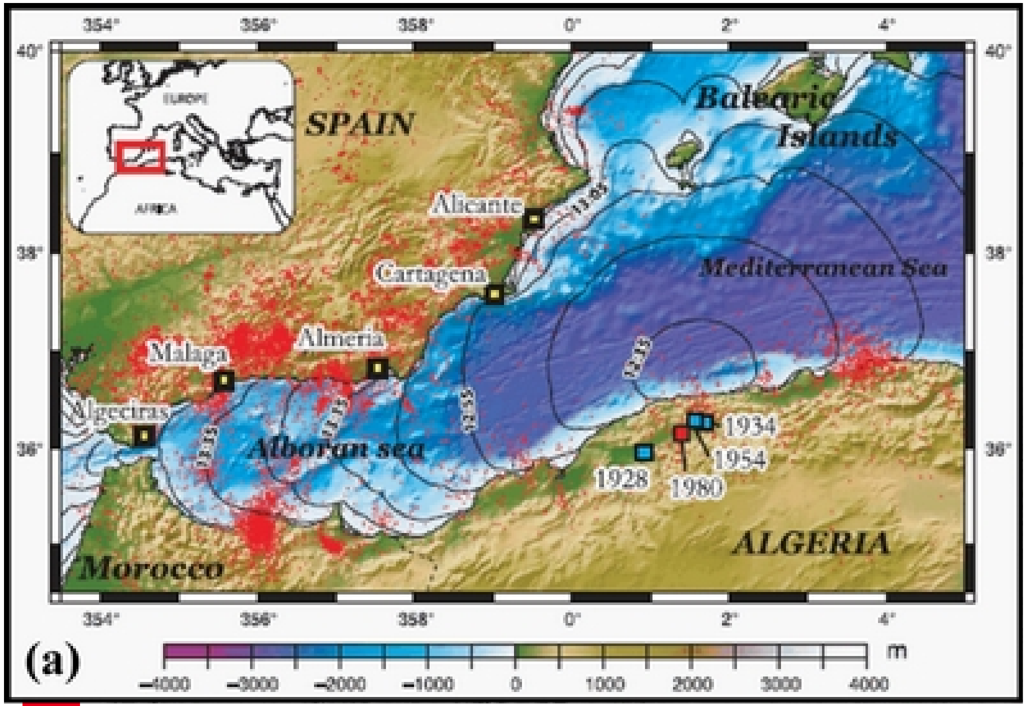


Warning map resulting from « on the fly » tsunami modeling using the source parameters of Tinti et al. (1999)

Example 4 : the 1980 El Asnam earthquake (Algeria, Ms=7.3)

Date: October 1980
Location: inland, along the Algerian margin, close to El Asnam.

Damages: one of the most destructive earthquakes recorded in northern Africa and the Western Mediterranean Basin. Followed by a small tsunami recorded on several tide gauges along the SE Spanish Coast (Cartagena, Almeria, Malaga, Algeciras, and Alicante, with amplitude of oscillations (peak to trough) of 48 cm).



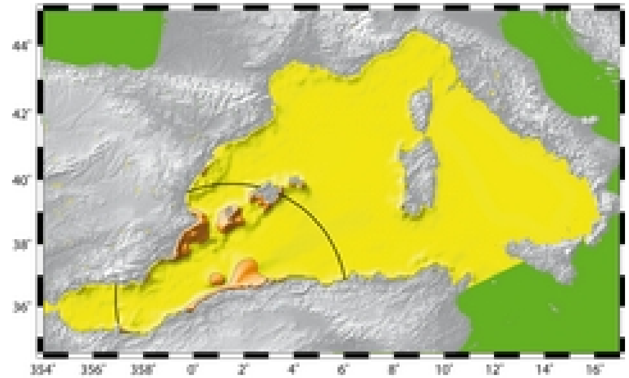
Approximate epicenter location of the major historical earthquakes in the area ***(from Roger et al., 2011)*****:**

[red square] -- Oct. 10, 1980; Ms~7.3

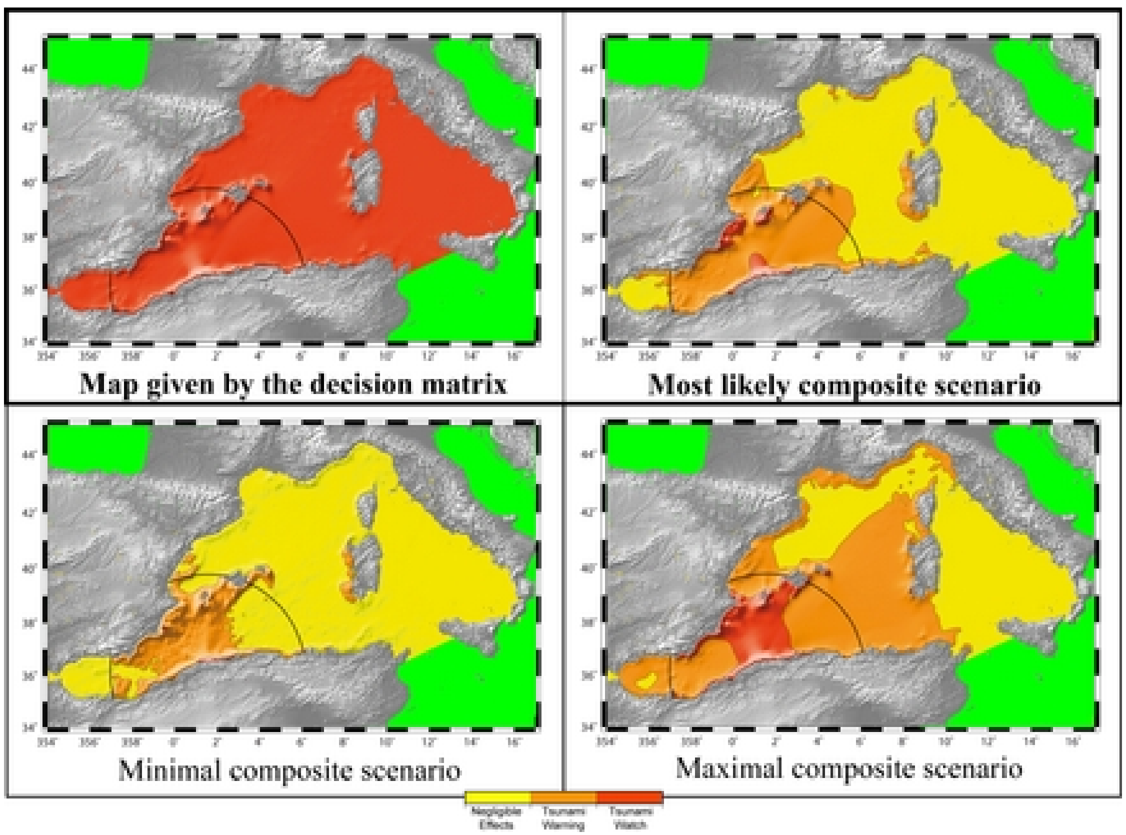
[blue squares] -- 1954 Orleansville and 1928 and 1934 events

[yellow squares] -- tide gauges that recorded the 1980 tsunami
[solid black curves] -- theoretical tsunami travel-times for a source located offshore El Asnam area

Example 4 : the 1980 El Asnam earthquake (Algeria, Ms=7.3)



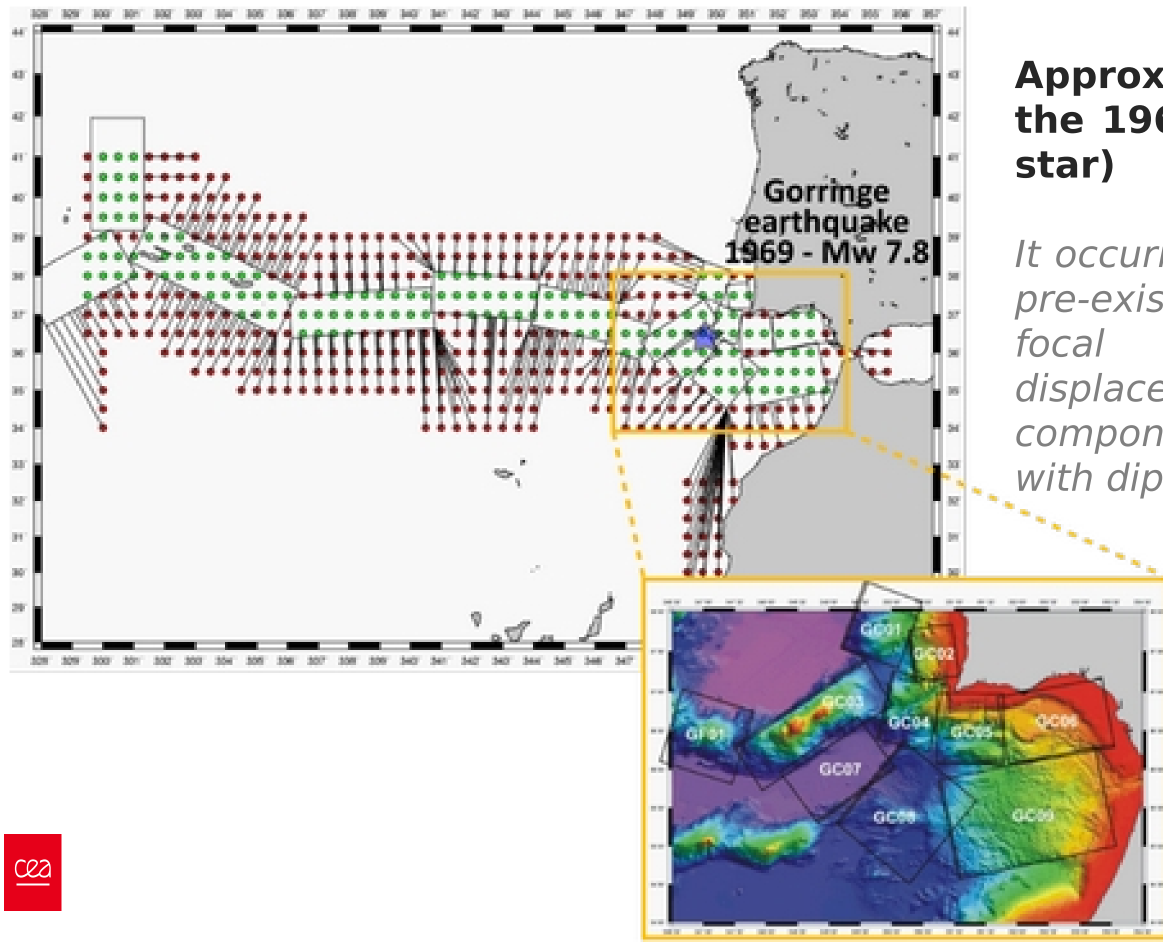
Warning map resulting from « on the fly » tsunami modeling using the source parameters of Roger et al. (2011)



Model-based tsunami prediction system

Example 5 : the 1969 Gorringe Bank earthquake (Atlantic, Mw=7.8)

Date: February 1969
Location: SW of Gorringe Bank beneath the Horseshoe Abyssal Plain.
Tide-gage measurements: Sea-level variations recorded in Portugal (up to 1.14m), Morocco and Spain

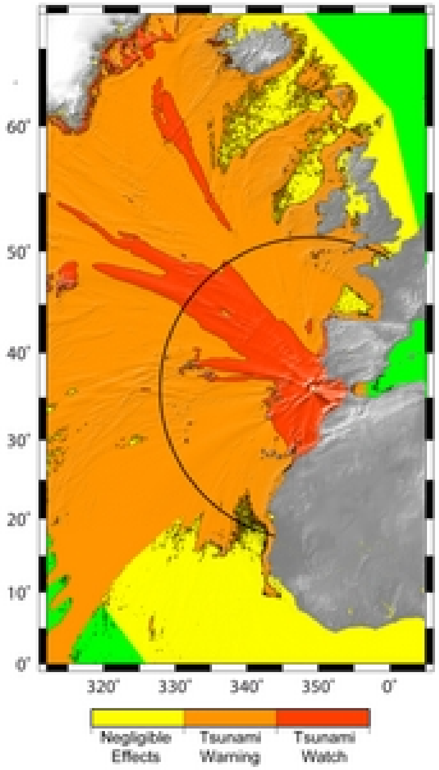


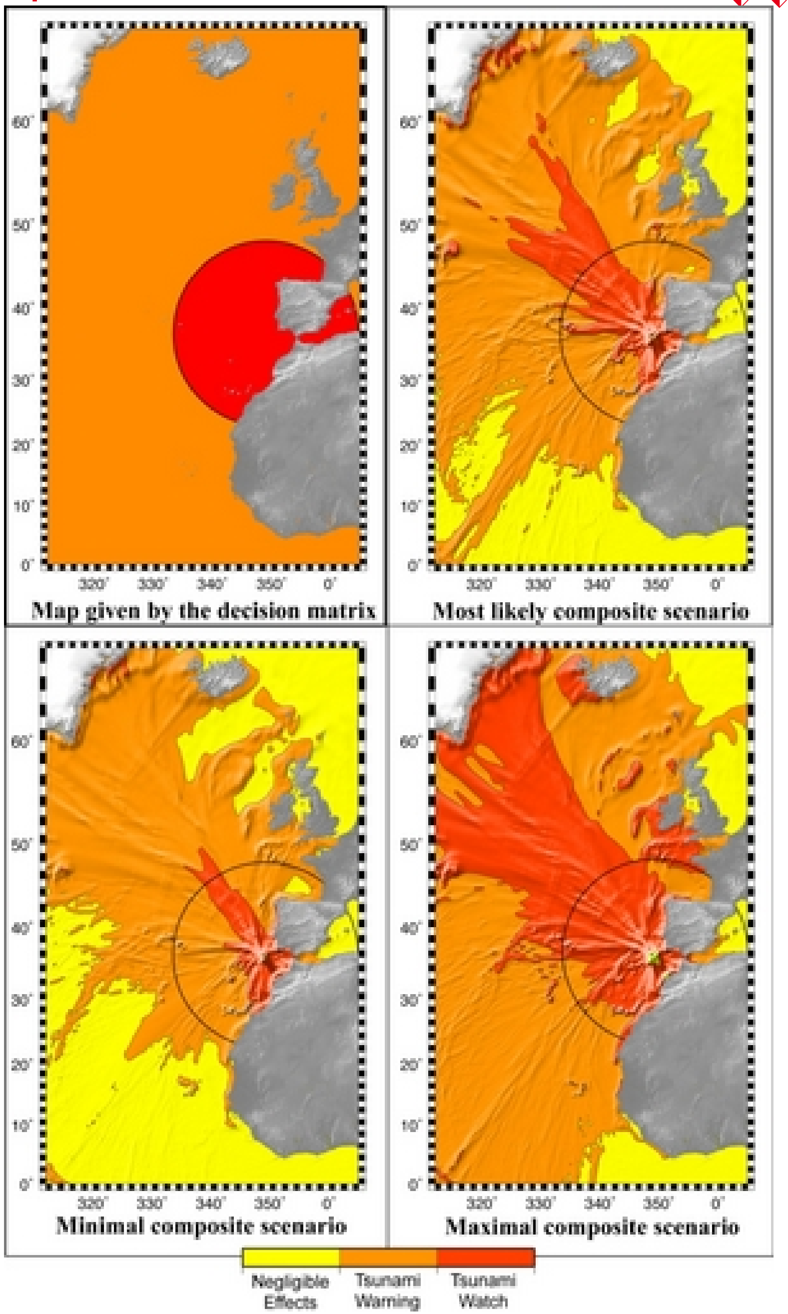
Approximate epicenter location of the 1969 Gorringe earthquake (blue star)

It occurred on a fault without pronounced pre-existing topography, although the focal mechanism showed reverse displacement with a minor strike-slip component (N35W striking fault plane with dip angle of 52°)

Example 5 : the 1969 Gorringe Bank earthquake (Atlantic, Mw=7.8)

Warning map resulting from « on the fly » tsunami modeling using the source parameters of Grandin et al. (2007)





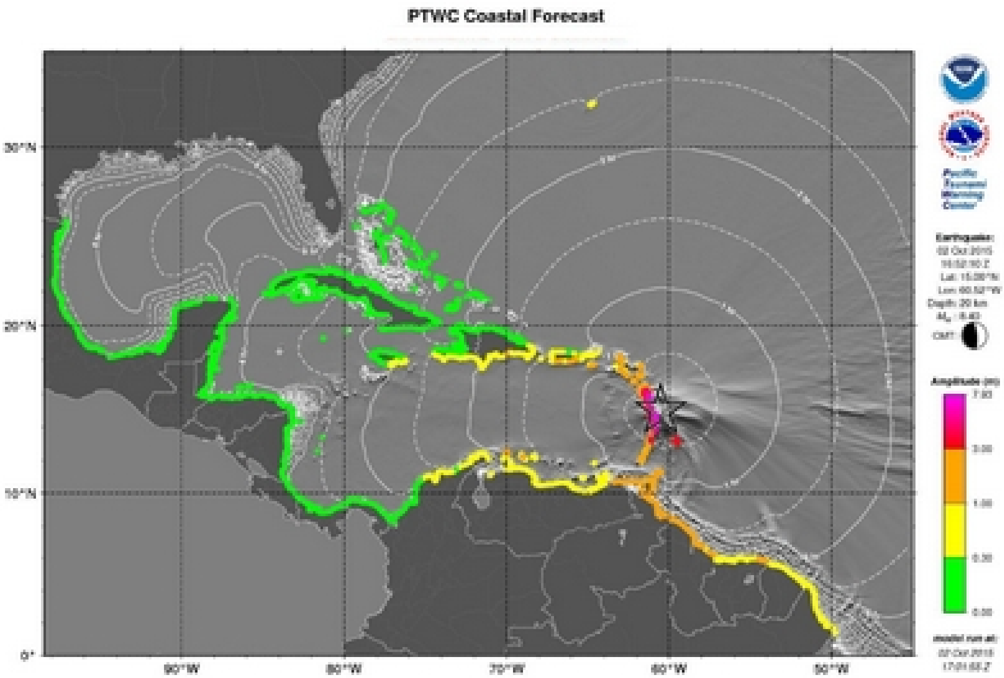
Model-based tsunami prediction system

Rapid forecasting methods for coastal impact estimate: Amplification laws

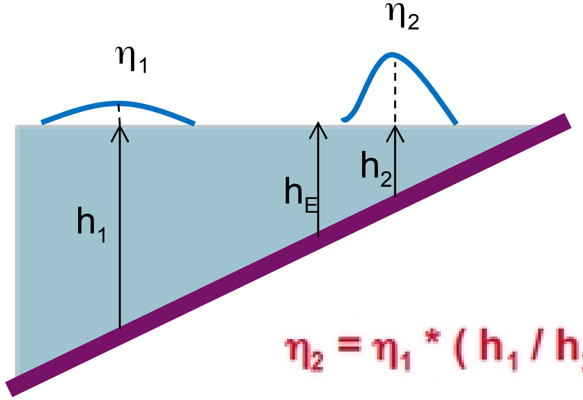
Tool for rapid prediction of water heights at the coast using amplification laws

Linear approximation of shoreline amplitude

expresses the conservation of wave energy flow by extrapolating the wave field meshed in the harbor at depth h2 from values calculated in deep water at depth h1.



PTWC coastal forecast map: individual forecast points colored according to the tsunami height expected at each coastal point.



$$\eta_2 = \eta_1 * (h_1 / h_2)^{1/4}$$

η_2 amplitude du tsunami en un point à la côte
η_1 amplitude du tsunami en un point au large
h_2 profondeur du point à la côte
h_1 profondeur du point au large

h_1 provient de la modélisation tsunami en océan profond (grille bathy grossière), généralement basée sur les équations shallow water linéraires.

Source : mécanisme au foyer ou base de scénarios pré-calculée.

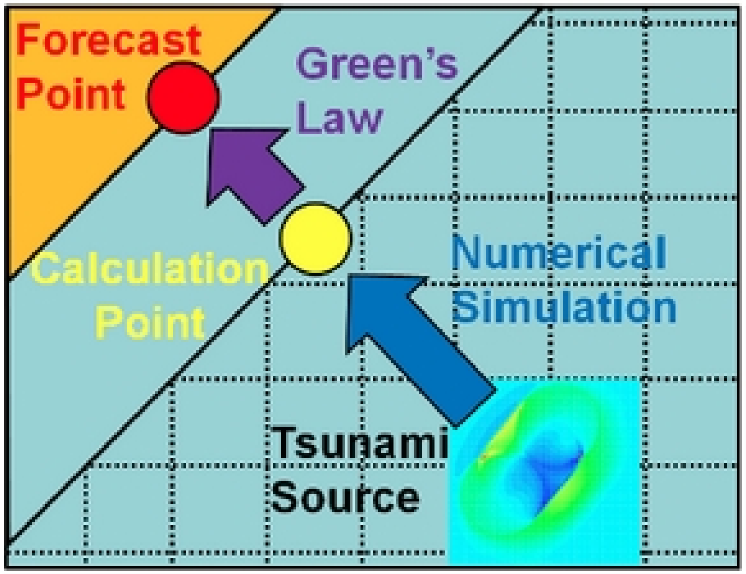
Limitations of pure Green's law (1837)

- Steep slopes, atolls and islands fringed by coral reefs

  => Overestimation of coastal amplitude.
- Resonant harbours and the influence of breakwaters

  => Underestimation of the actual wave amplitude, as the complex response of a particular port does not follow exactly the law.
- Anticipated coastal amplitude not indicative of flood depth (depends on local topography).

  => A coastal amplitude of 30 m according to Green's law does not mean that the flood depth will reach 30 m. But very significant impact.
- Near-field wave dissipation not taken into account.



Tool for rapid prediction of water heights at the coast using **adapted** amplification laws

Linear approximation of shoreline amplitude

- Two transfer functions using a tested correction factor
  - Green's law (1837) modified by Reymond et al. (2012)
  - Law from Lalli et al. (2019)
- Robust calculation of the correction factor (Giles et al., 2022)
  - Cost function minimization by gradient descent.
- Error bars on calculated values: factor 2
  - Equivalent results with both types of law

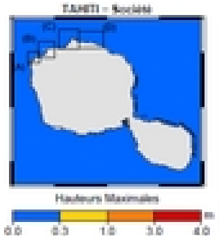
Advantages

- Resultats within 5 minutes
- Reduction of the scenario base required to calculate the correction factor

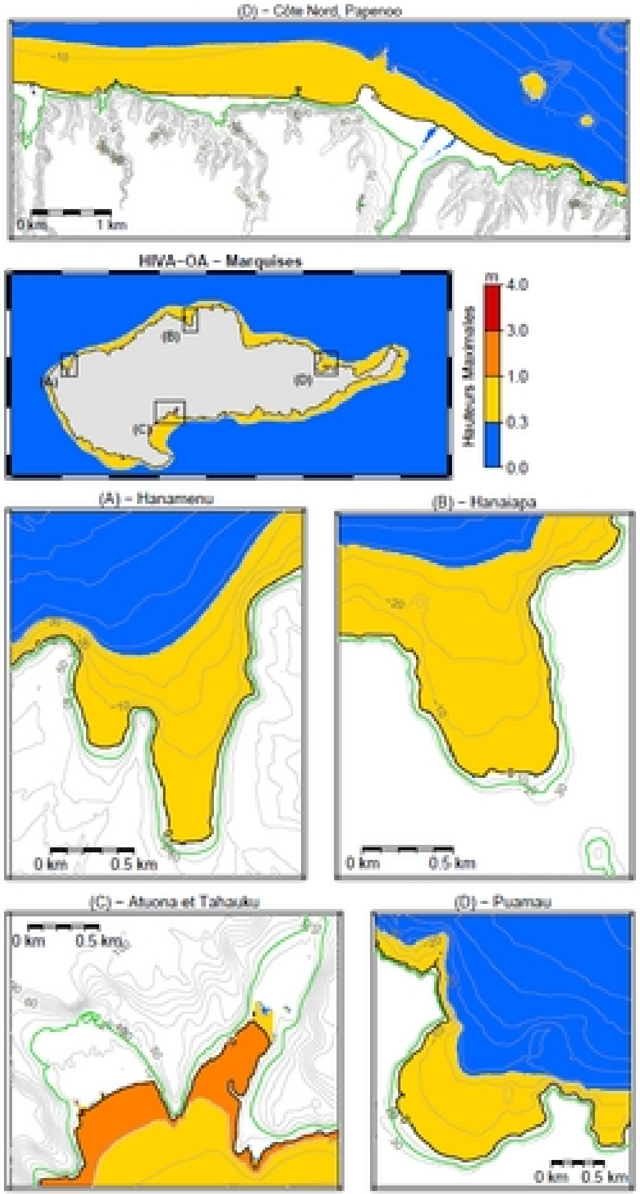
Disadvantages

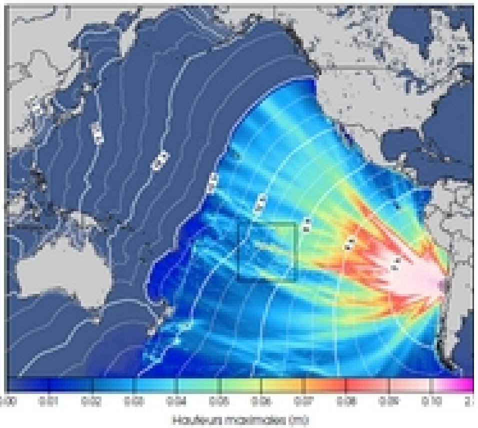
- Limited consideration of local effects
- No run-up estimate

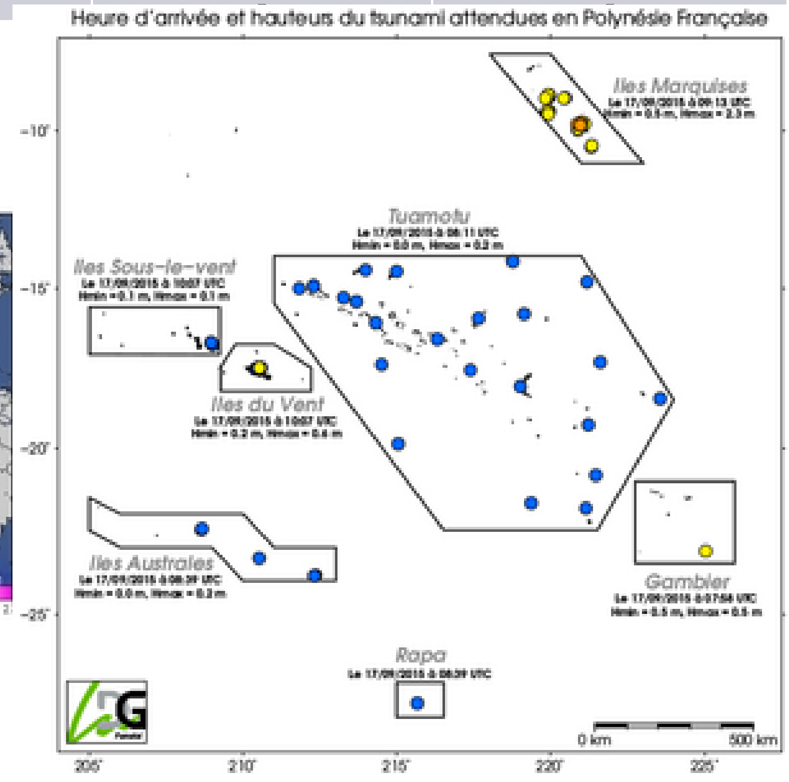
CPPT – MERIT alert maps for the September 16, 2015 tsunamigenic earthquake in Chile (Mw 8.1)

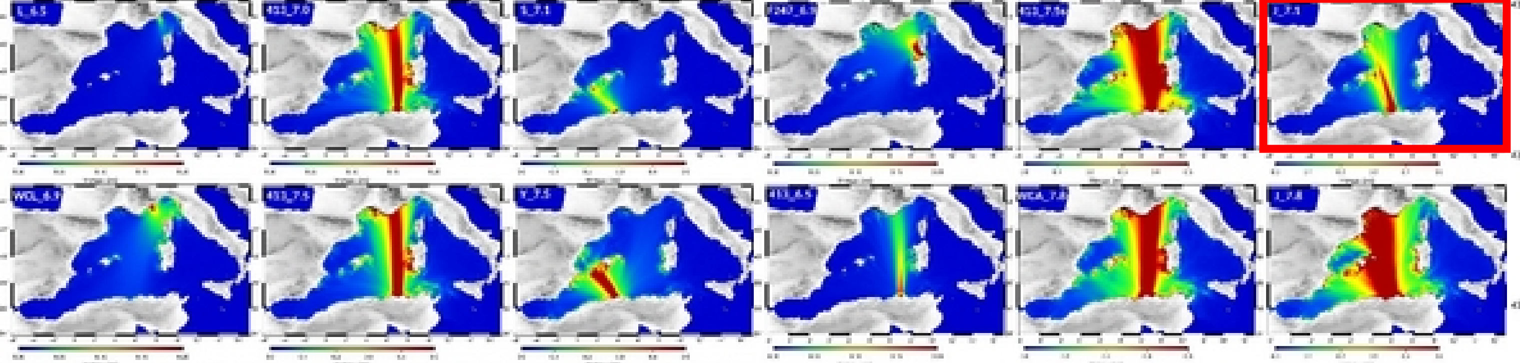


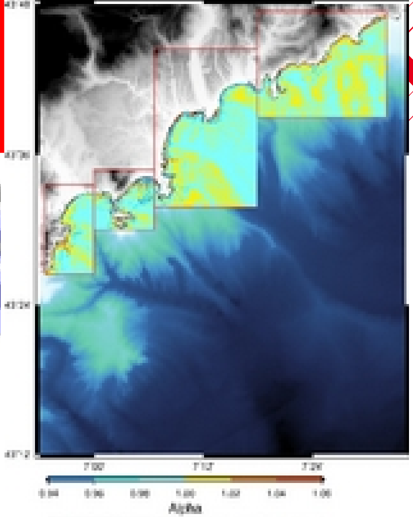
Archipel/ Region	Première heure d'arrivée théorique le 2015/09/17 (UTC)	Hauteurs maximales Simulation type Normale	Hauteurs maximales Simulation type Compacte
Iles Australes	08:47	0.1 – 0.2 m	0.1 – 0.2 m
Gambier	08:06	0.1 m	0.1 m
Iles Marquises	09:20	0.5 – 1.3 m	0.5 – 1.4 m
Tuamotu	08:19	0.2 – 0.3 m	0.3 m
Iles du Vent	10:15	0.2 – 0.6 m	0.2 – 0.8 m
Iles Sous-le-Vent	10:15	-	-
Rapa	08:47	[illegible]	[illegible]



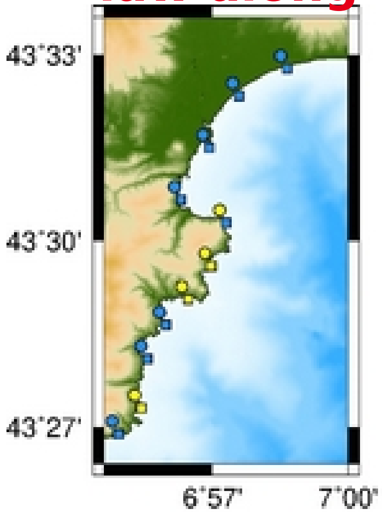


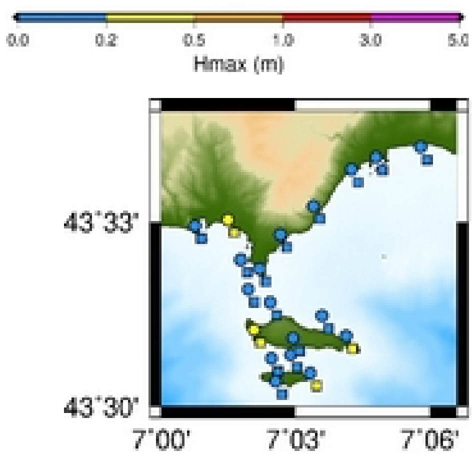


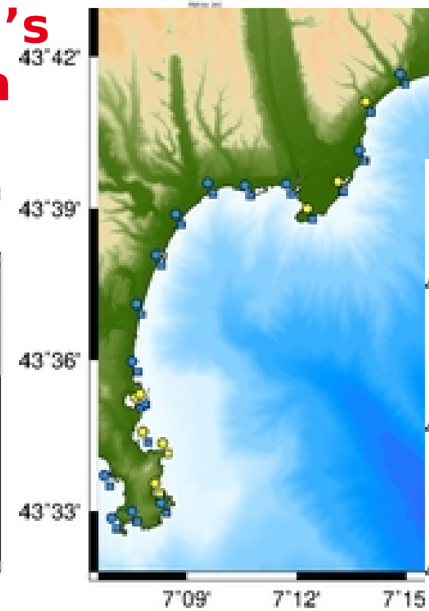


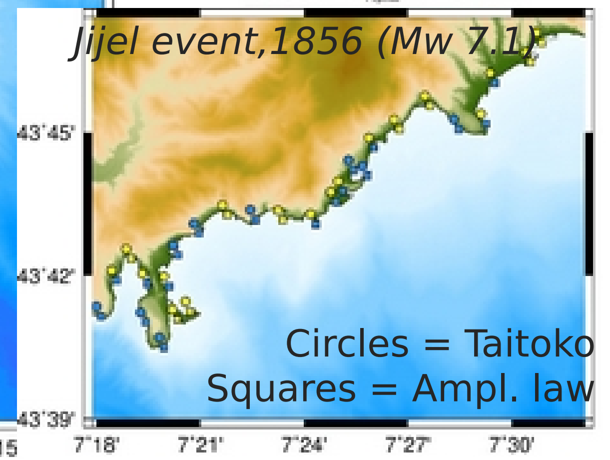


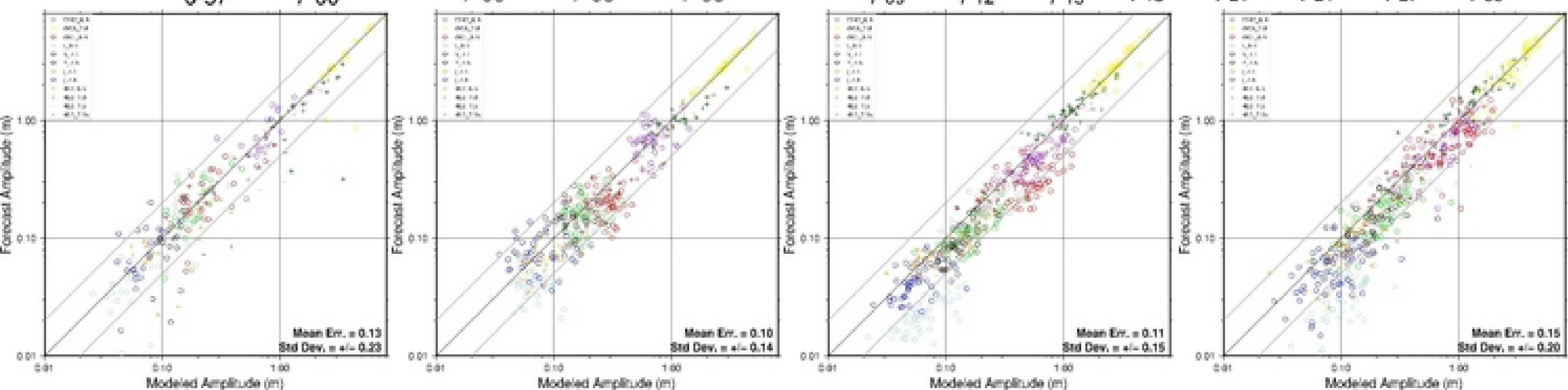
Example of forecast with Lalli's law along the French Riviera











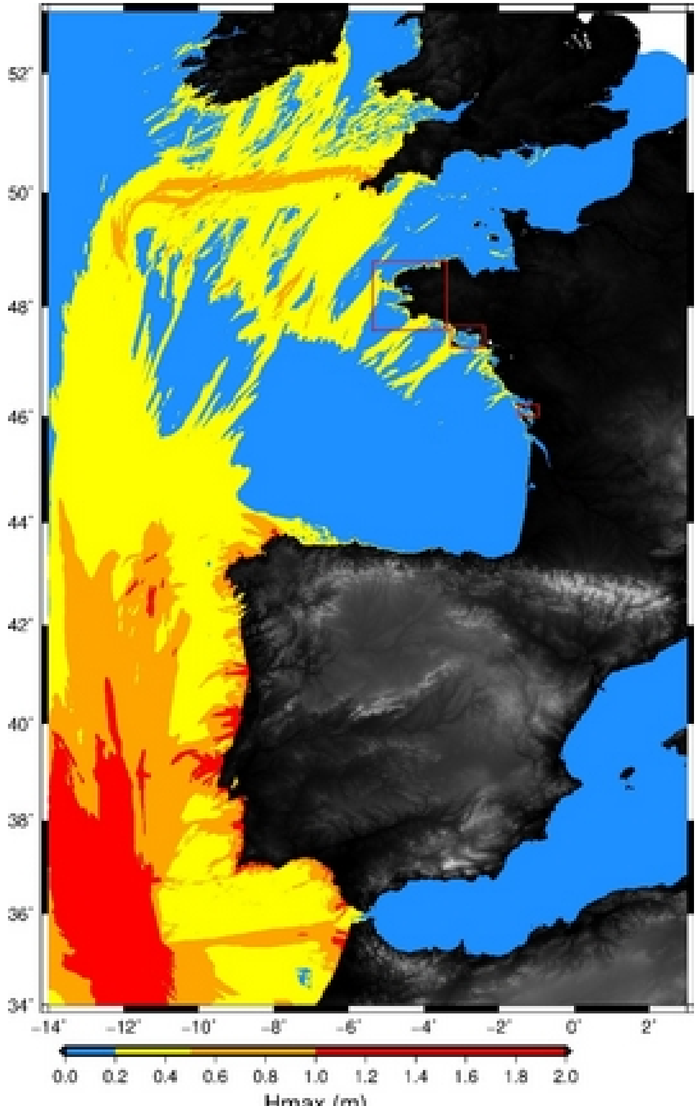
NEAMWAVE23 exercise : CASSIOPEE – Taitoko – Coastal Forecasting Law comparison

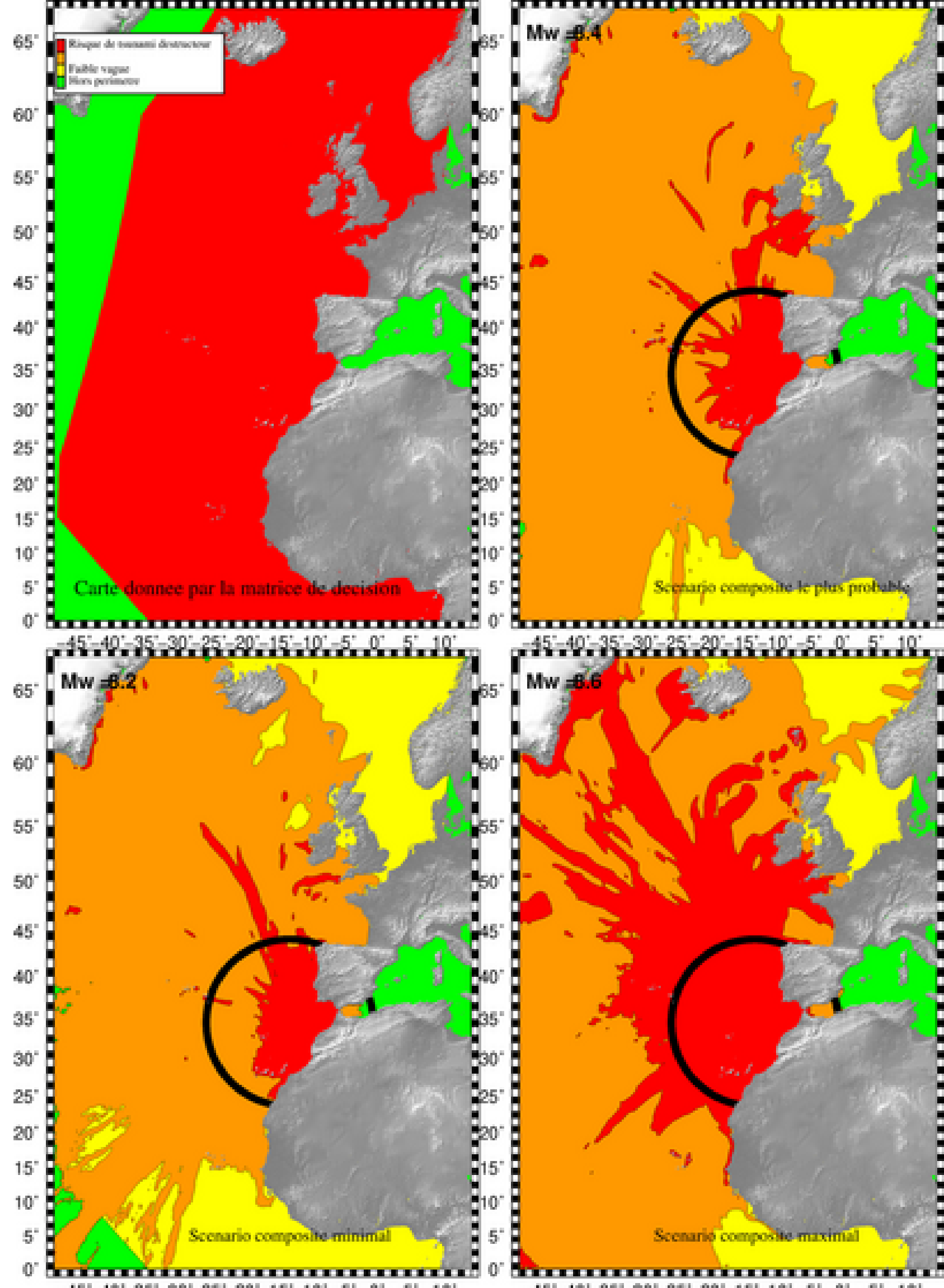
- 1761 Gloria Fault earthquake (Atlantic) – Mw ~ 8.4-8.5

HYPOTHESIS A (MW 8.4)

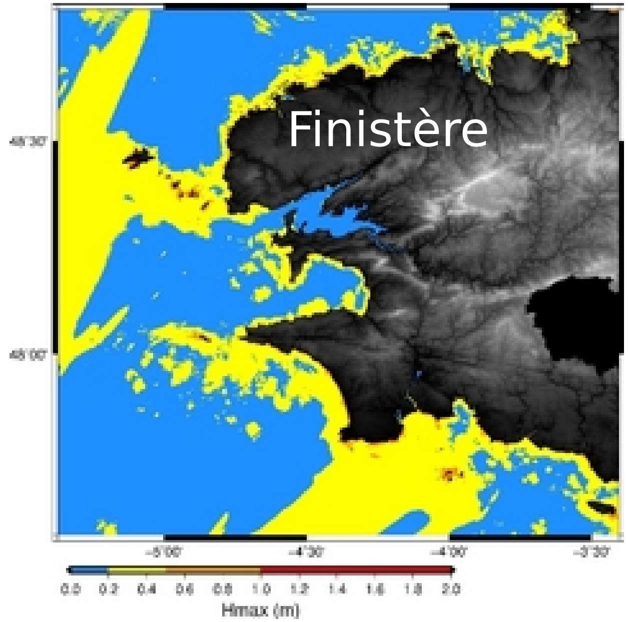
Scenario	L (km)	W (km)	Strike (°)	Dip (°)	Rake (°)	Slip (m)	Depth (km)	Mag.	μ (Pa)	Focal mechanism
Hyp. A-MS	4 × 50	50	76	40	135	7/15/15/8	10	8.4	4×10^{10}	
Hyp. A	200	50	76	40	135	11	10	8.4	4×10^{10}	
Hyp. B	280	50	254.5	70	45	15	10	8.5	4×10^{10}	

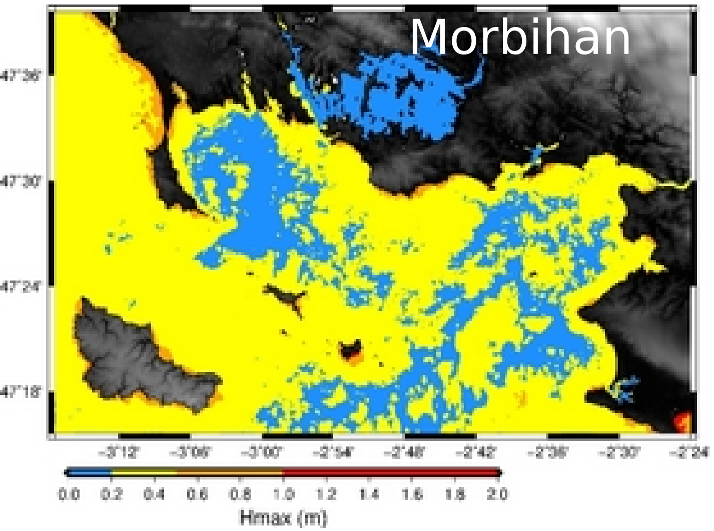
Wronna et al. (2019)

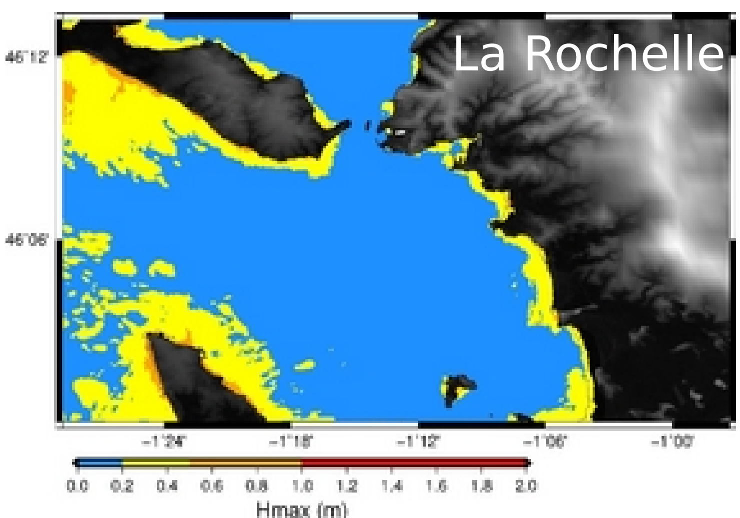


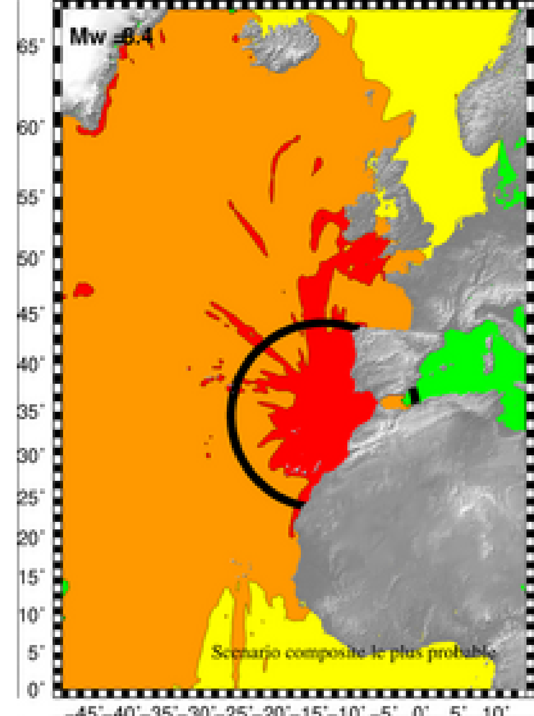


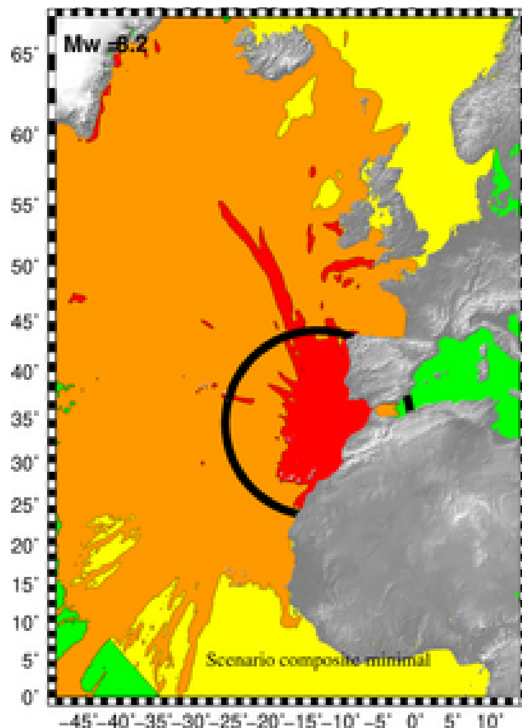
HYPOTHESIS A (MW 8.4)
-
Comparison CASSIOPEE with Taitoko at 20 m resolution

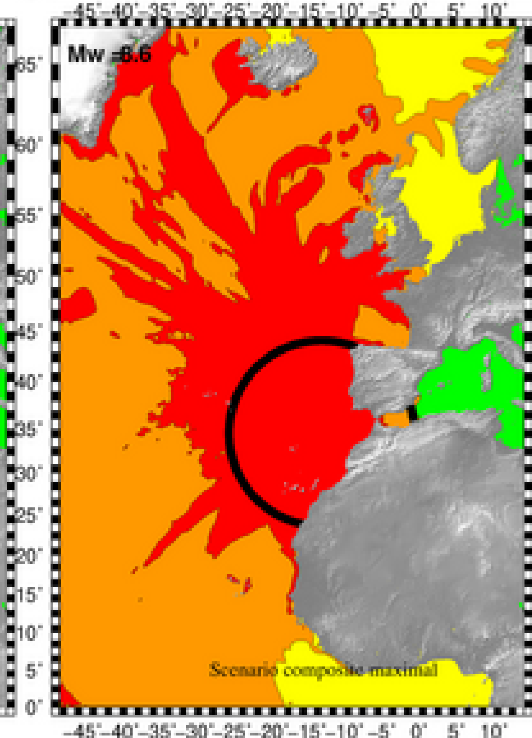




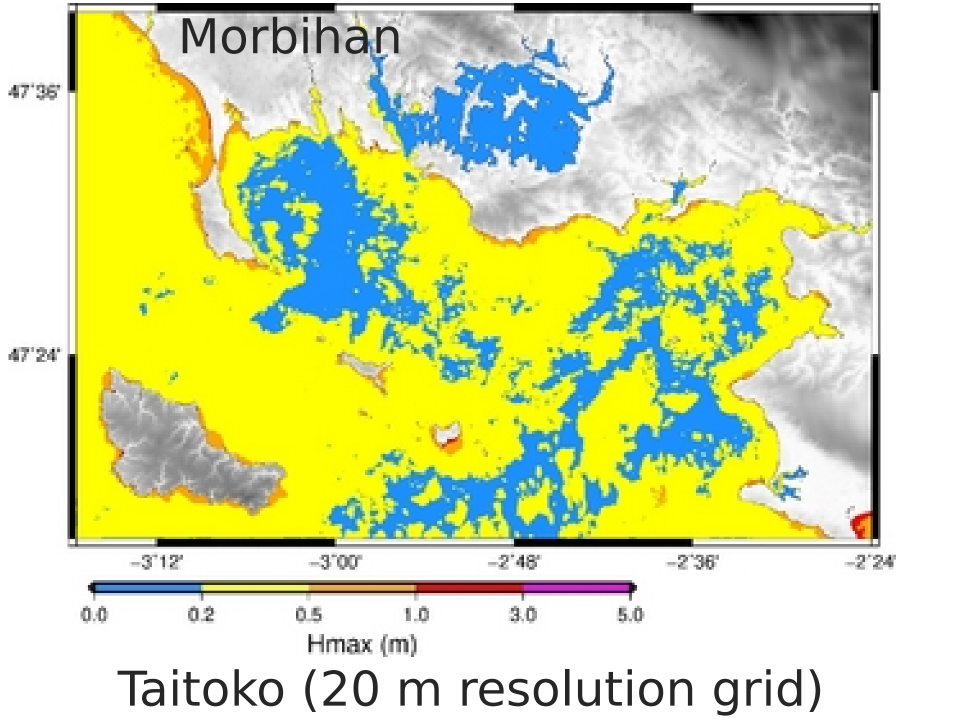


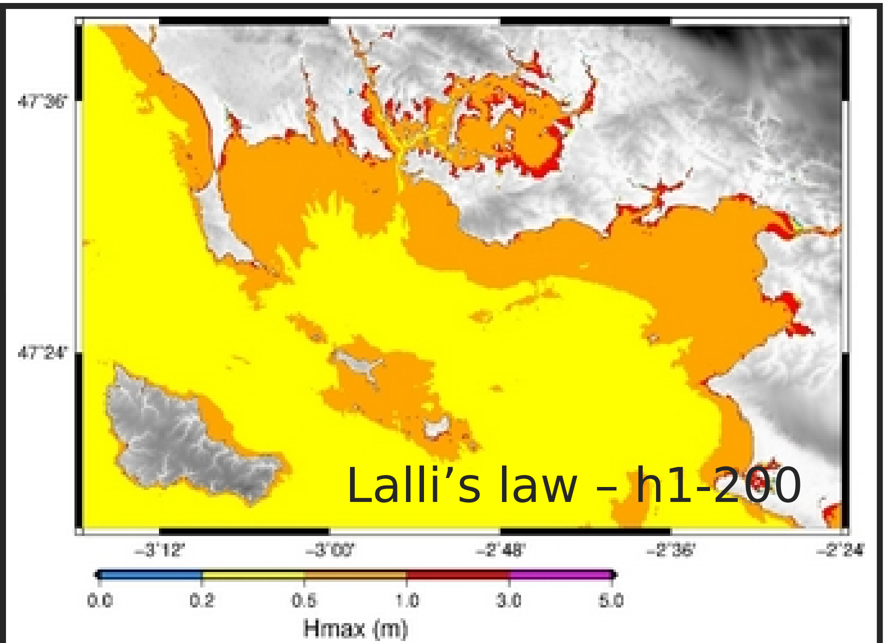


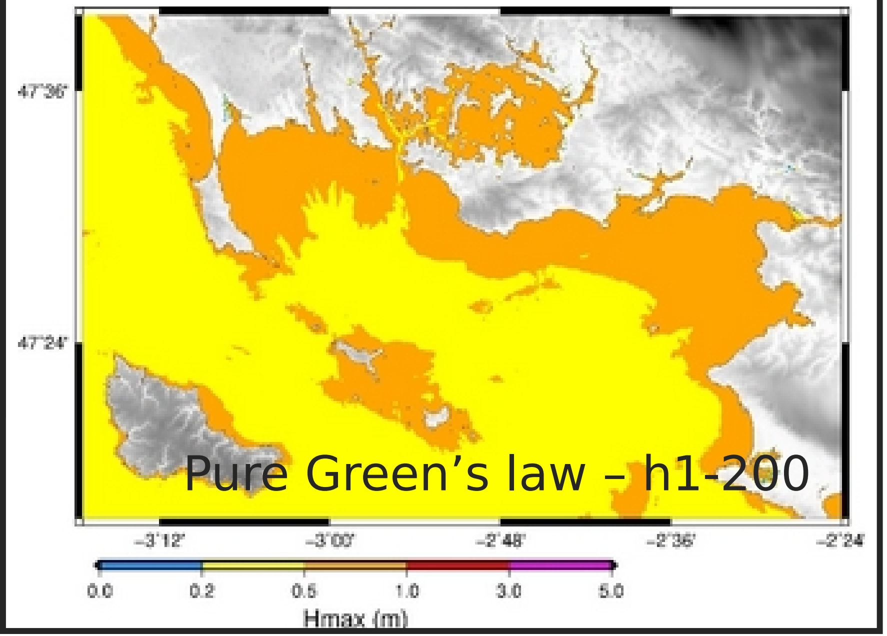




HYPOTHESIS A (MW 8.4)
-
Comparison amplification laws with Taitoko at 20 m resolution







Forecasting with AI

Machine learning techniques for rapid coastal flood forecasting

Newly explored approaches to tsunamis (e.g., Fauzi & Mizutani, 2020 ; Mulia et al., 2020)

Objective: rapidly transform a deep ocean simulation result into a coastal flooding model.

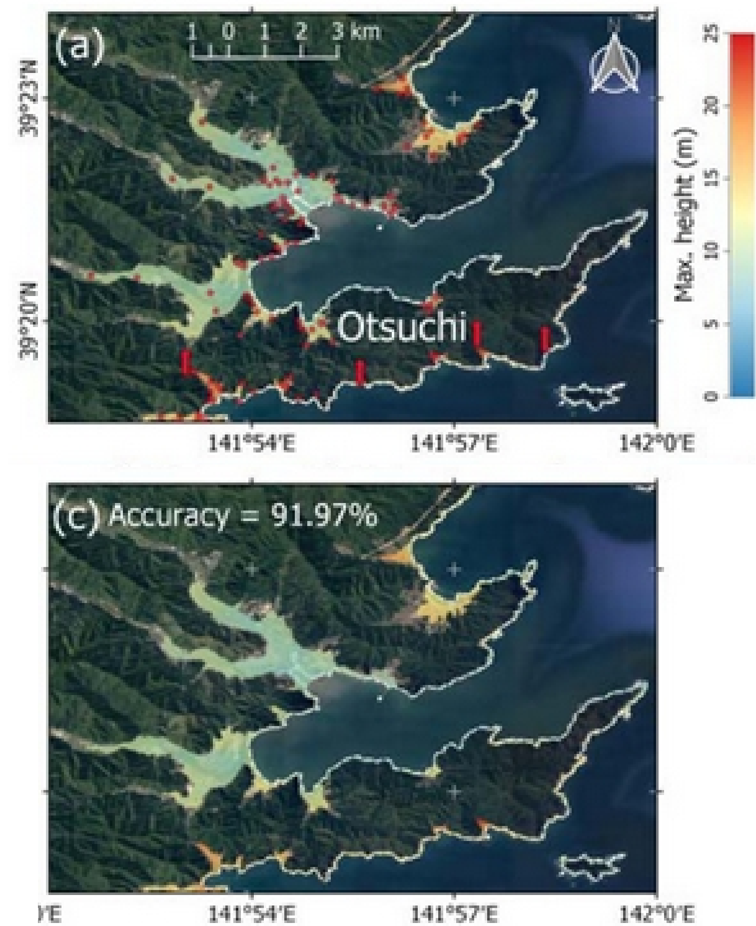
- Adding complexity to predicted models
  - Maximum height and run-up, maximum shrinkage, currents
- Several techniques, treatments and parameters explored
  - Several architectures tested
  - Reduction of input dimensions; adjustment of hyperparameters

Advantages

- Results within 1 seconde
- Consideration of inundation and local effects
- Adding uncertainties to predictions

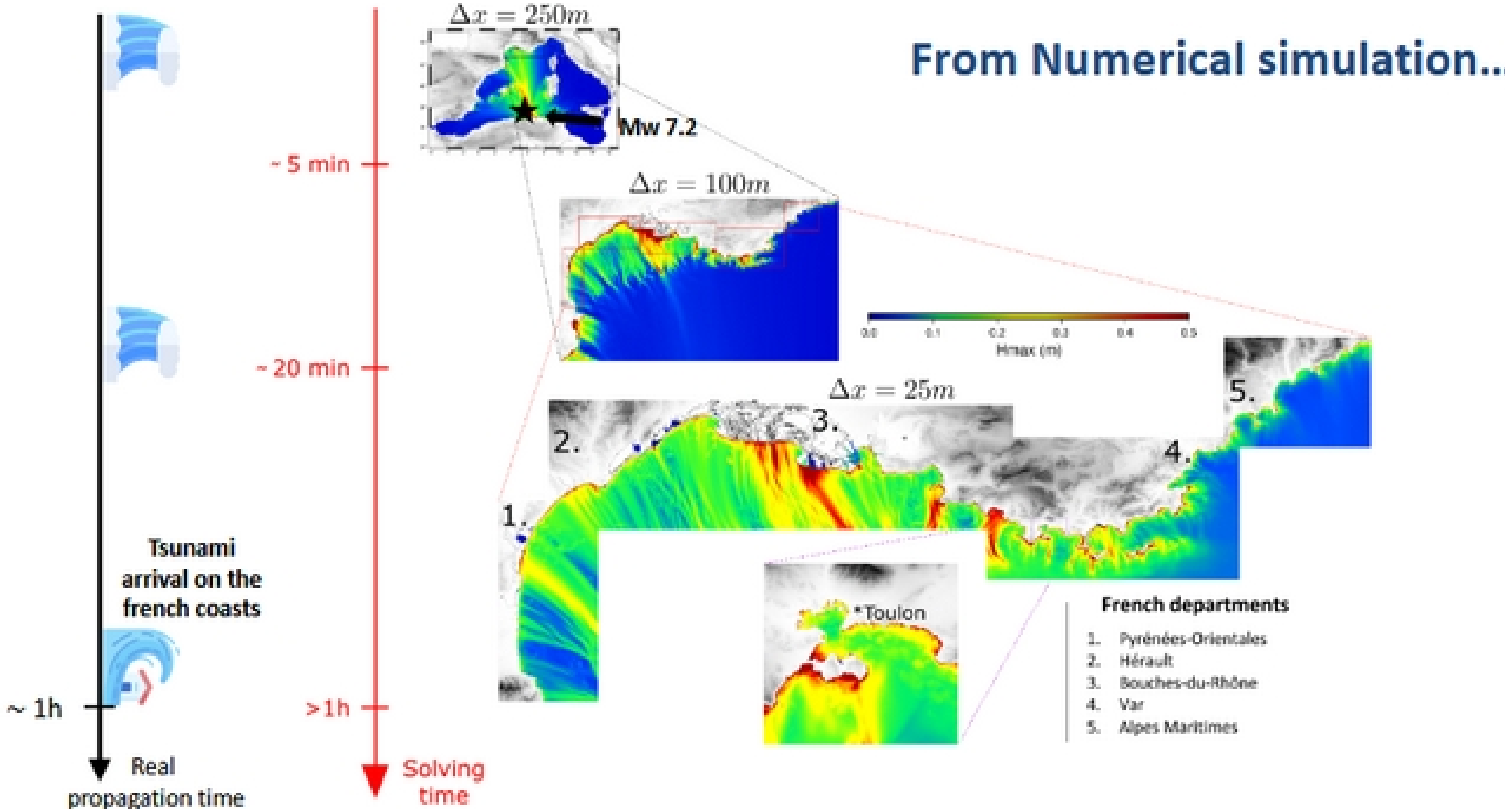
Disadvantages

- Grid size limitation
- Wide range of learning scenarios database needed

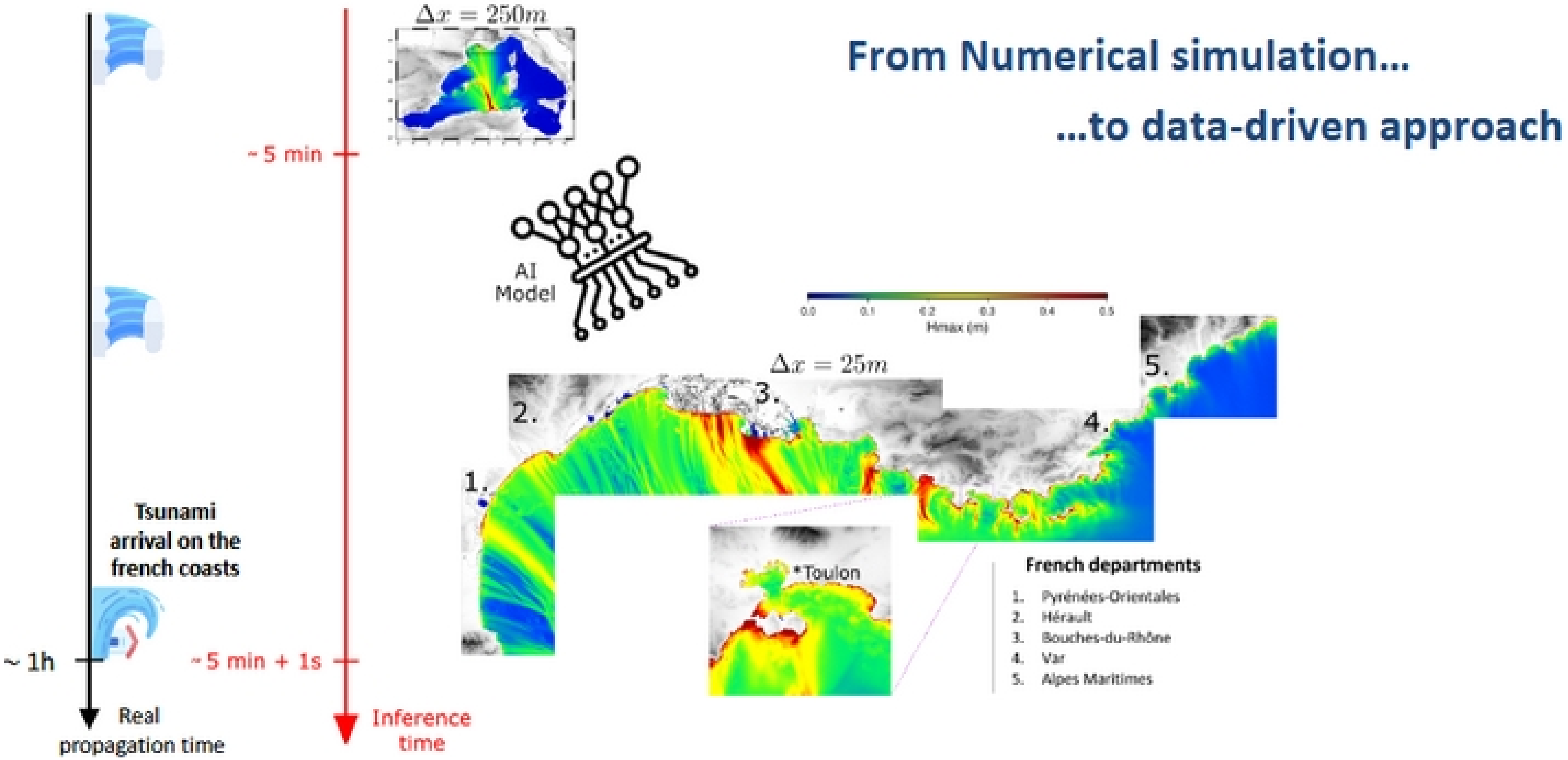


Simulated maximum flood heights at Otsuchi (Mulia et al., 2020). [a] Reference numerical simulation. [c] DNN result (accuracies calculated with respect to [a]).

Problem and dataset



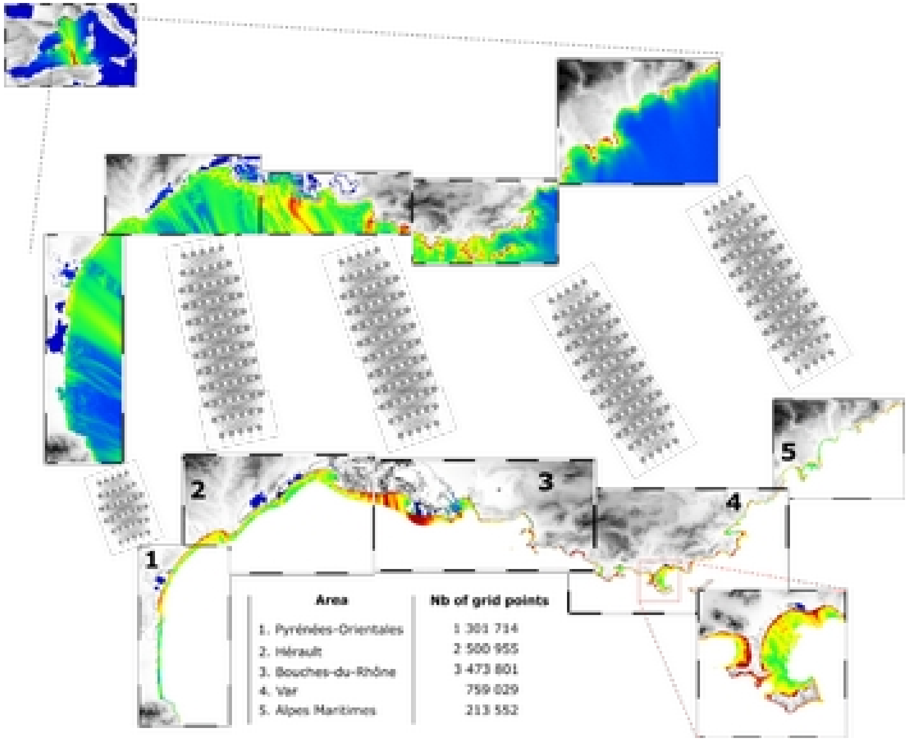
Problem and dataset



Application of deep neural networks

Data driven model to learn the mapping between low and high resolution maps

Target area	the entire French Mediterranean coast*
Target output grid resolution	25m
Nb of output grid points	8 000 000



*except Corsica island :c

Dataset specification

Dataset

Description of the dataset :

- **Hypothetical** scenarios with magnitudes between **5.7** and **7.8**
- Generated from **z03** and **z04 zones**
- Integrating **heterogeneous** faults with stochastic slip distribution
- Only scenarios giving at least **3cm** inundation heights retained

Amount of data :

- **1866** scenarios
- **1h/sim**. run on 1024 Intel Broadwell 2.4 GHz cores
- 70% for the training dataset
- 20% for the validation dataset
- 10% for the testing dataset

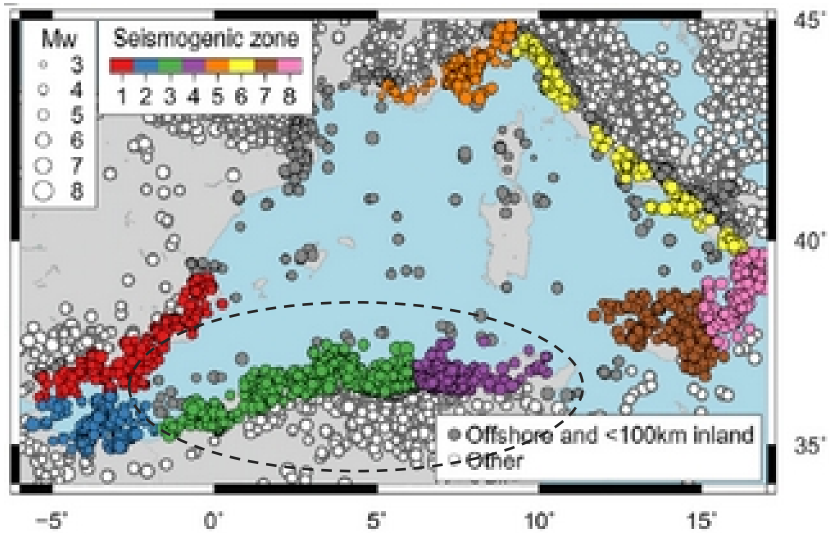
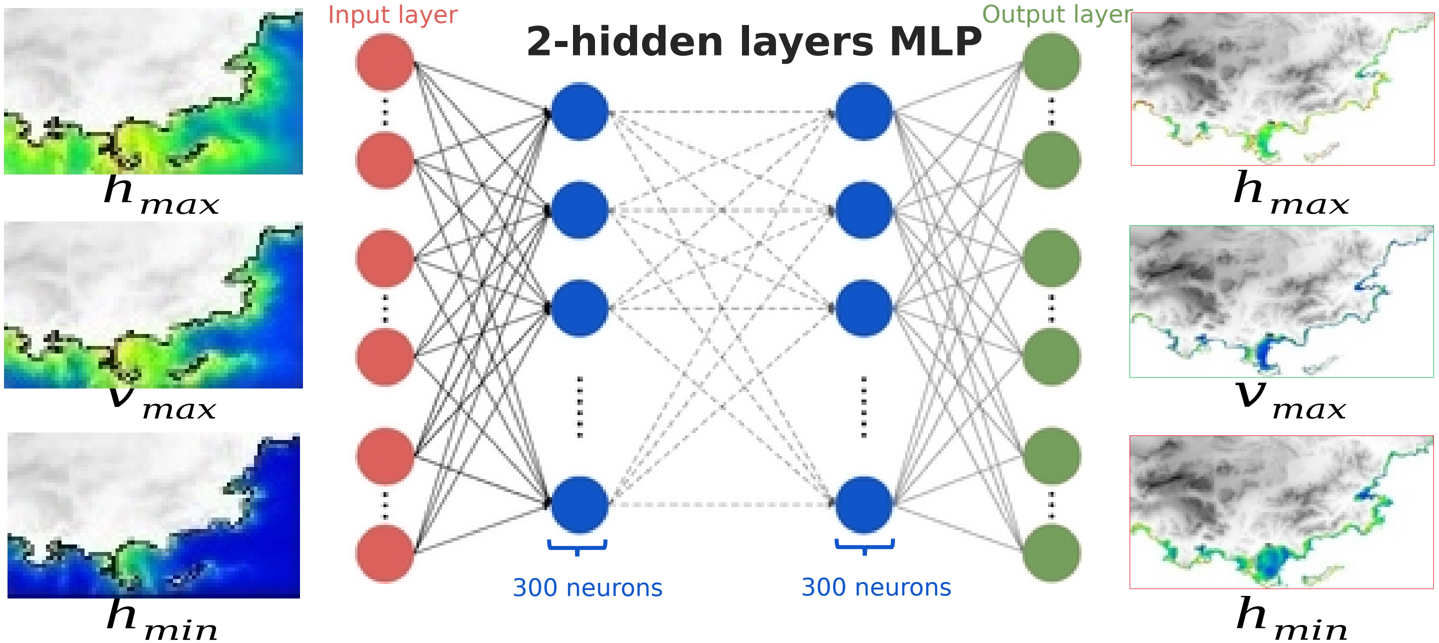


Figure 2 : Repartition of the earthquakes (Mw > 3) within the WM basin. Colored circles show earthquakes located in the seismogenic zones (one color per zone). z01: South Eastern Spain; z02: Northern Morocco; z03: Northern Algeria; z04: Northern Tunisia; z05: Ligurian Coast; z06: Western Italy; z07: Sicily; z08: Calabria. [5]

First model : MultiLayer Perceptron (MLP) Neural Network

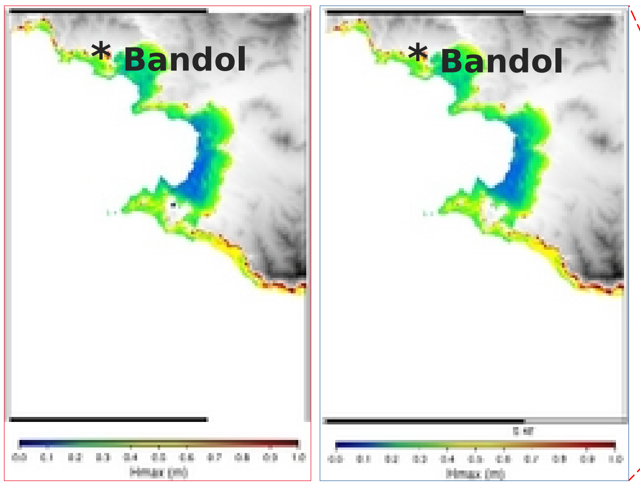


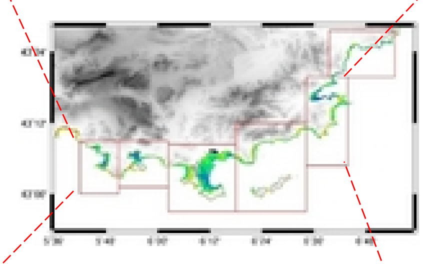
Input coarse grids :
Grid resolution = 250m
Nb of grid points :

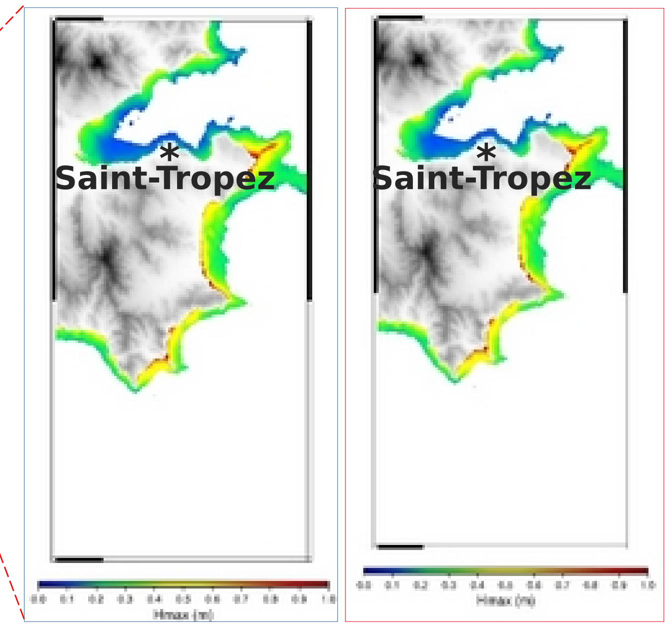
Output fine grids :
Grid resolution = 25m
Nb of grid points :

Deep neural network results

Results in Var coasts for a 7,2 Mw earthquake in z04 region

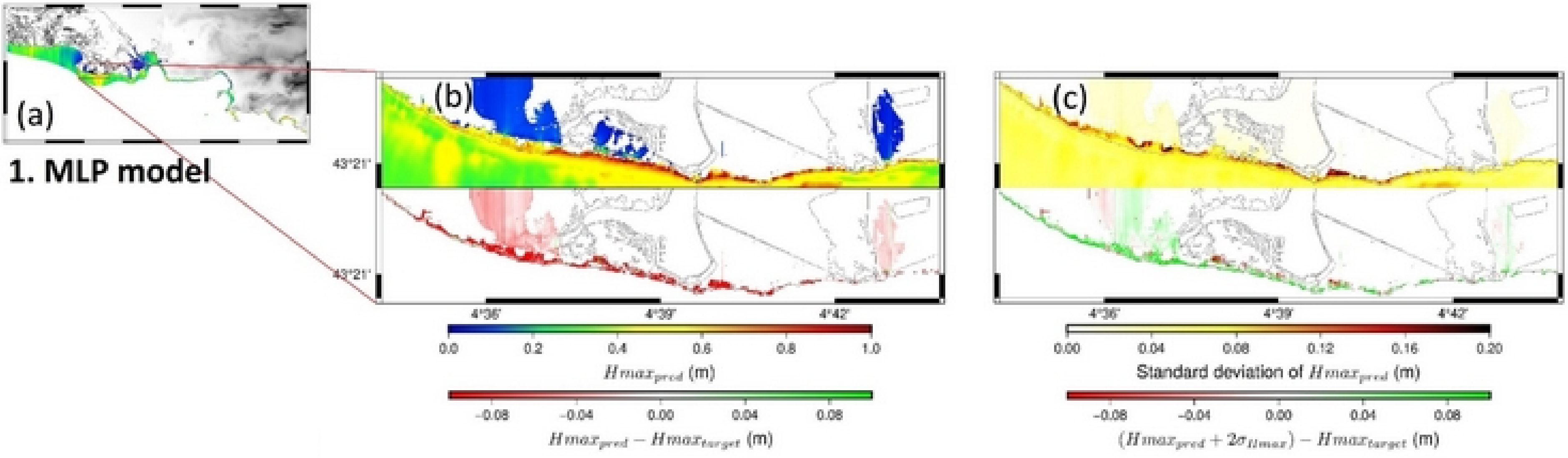






Reference vs NN prediction

Uncertainty quantification in ML models



Hazard assessment mapping: deterministic vs probabilistic

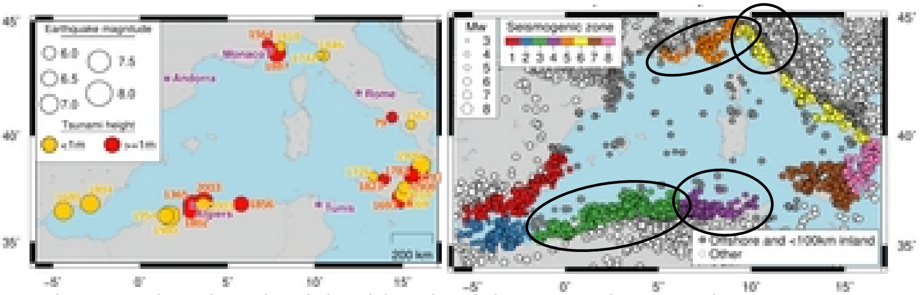
Probabilistic Tsunami Hazard Assessment (PTHA)

Studies in Europe:

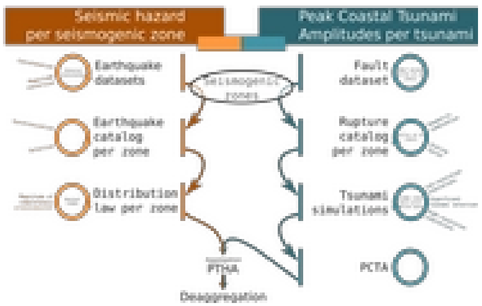
- S-PTHA at basin scale + Green's law : Sorensen et al. (2012), Lorito et al. (2015), Glimsdal et al. (2019), Basili et al. (2018, 2021)
- S-PTHA High Resolution (Italy): Volpe et al. (2019), Gibbons et al. (2020)
- *PTF (Italie): Selva et al. (2021)*

High-Resolution Seismic-Probabilistic Tsunami Hazard Assessment (S-PTHA) along the French Mediterranean coastlines

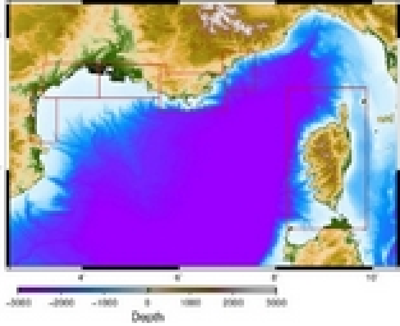
H2020-Euratom NARSIS PROJECT
(2017-2021)
(New Approach to Reactor Safety ImprovmentS)



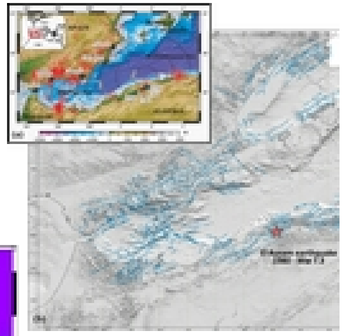
a)Tsunamigenic seismicity. b) Seismicity per Seismogenic zone



Overview of the method (from Souty & Gailler, 2021).

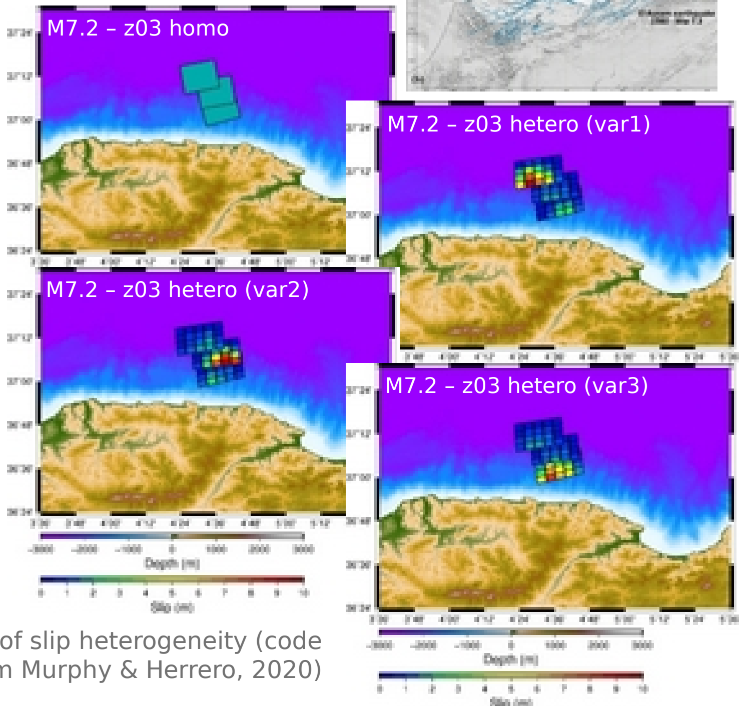


Extent of target zones at 25 m resolution (red rectangles) based on bathy-topo Litto3d® data.

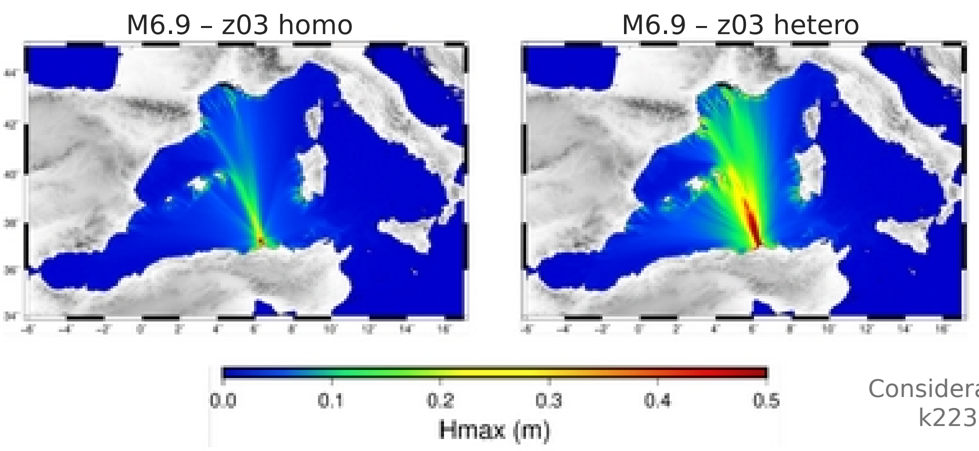


Approach

- S-PTHA HR optimized in computation time, site independent method
- Scenarios based on CENALT faults and seismogenic zones
- Integration of heterogeneous sources, application to the entire French Mediterranean coastline



Consideration of slip heterogeneity (code k223d from Murphy & Herrero, 2020)



Contribution of high-resolution grids to probabilistic estimation along the French Mediterranean coastlines, compared to pure Green's law

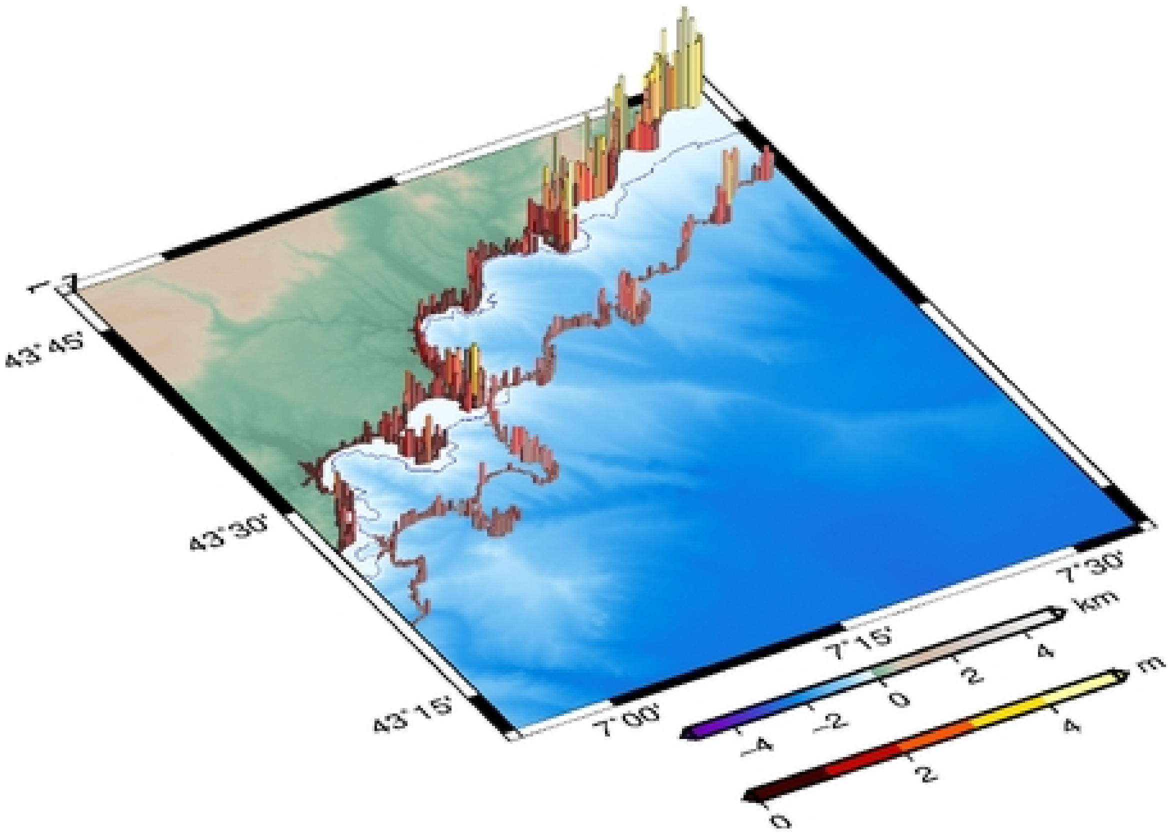
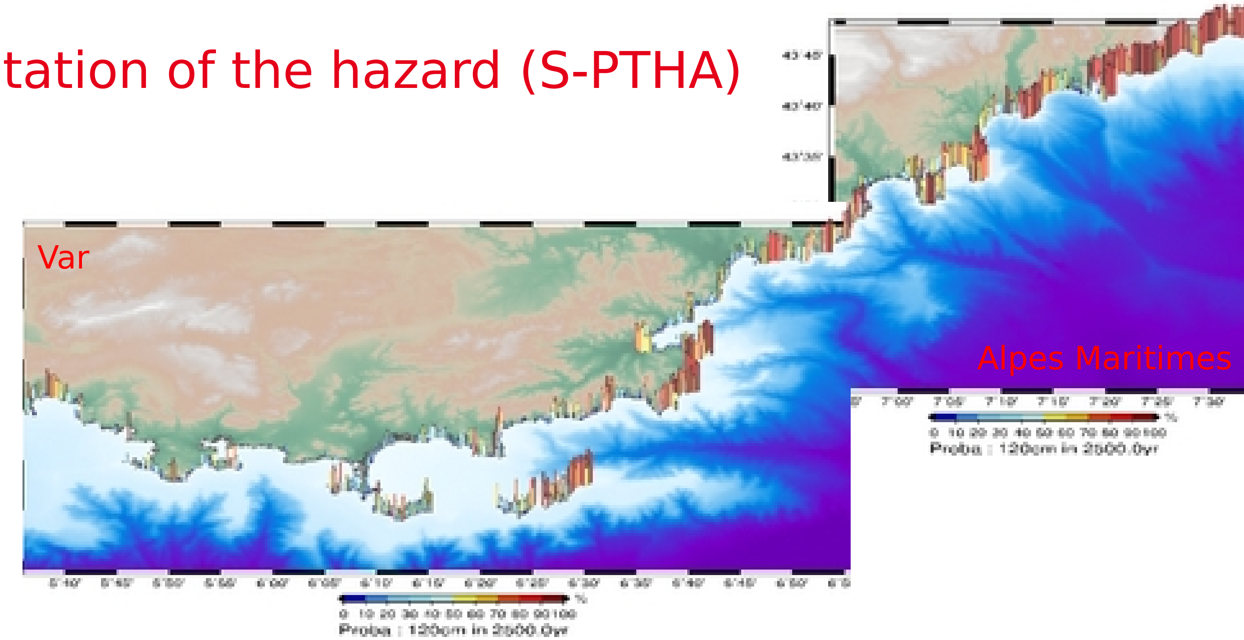
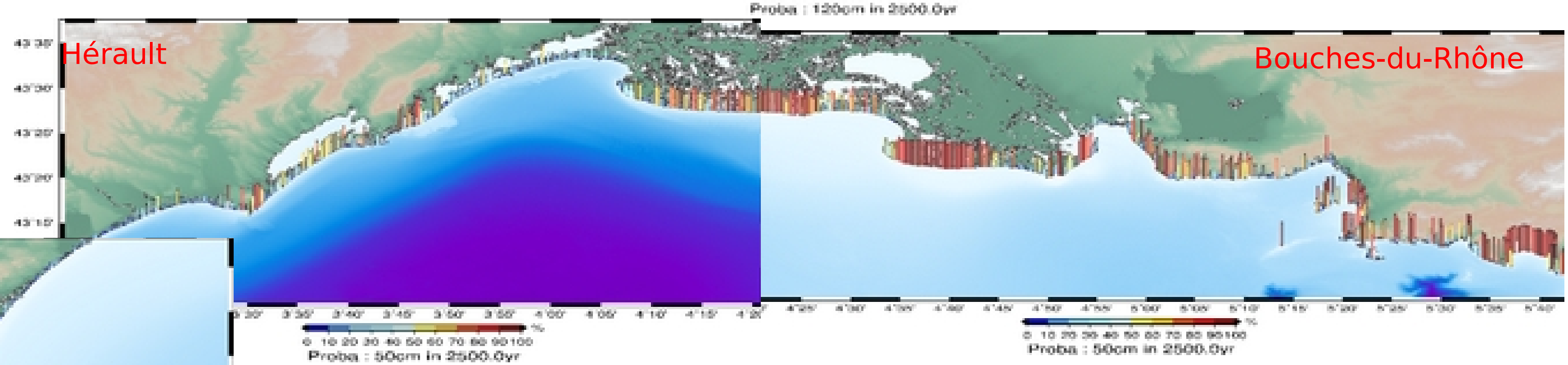


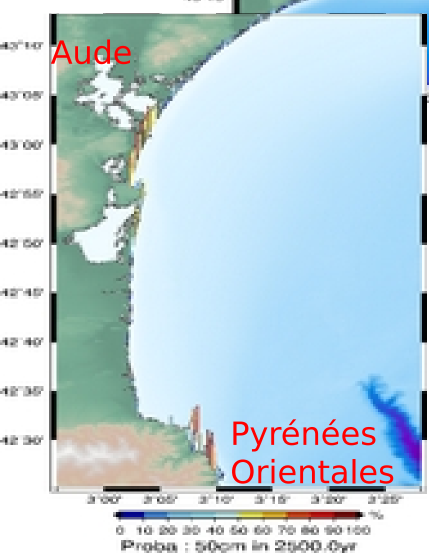
FIGURE 4.2 – Comparaison des h_{max} et $h_{max,apriori}$ pour la grille AlpesM de 25 m (isobath 1 m), pour un événement M_w7.4 de la zone z05 constitué de 3 sources unitaire. Les h_{max} sont placé sur l'isobath 1m (bord foncé). Les $h_{max,apriori}$ son placé plus en avant de l'image (bord clair). L'isobath 100 m est tracé en bleu.

HR Probabilistic representation of the hazard (S-PTHA)

H2020-Euratom NARSIS PROJECT
(2017-2021)
(New Approach to Reactor Safety ImprovmentS)







Probability of occurrence of waves with a maximum height of 0.5 m to 1.2 m over a 2500yr period, considering the seismogenic zones of the Algerian margin (z03+z05) and the Ligurian Sea (z05+z06) along the French coastline at 25 m res.

Probability over 2500 years

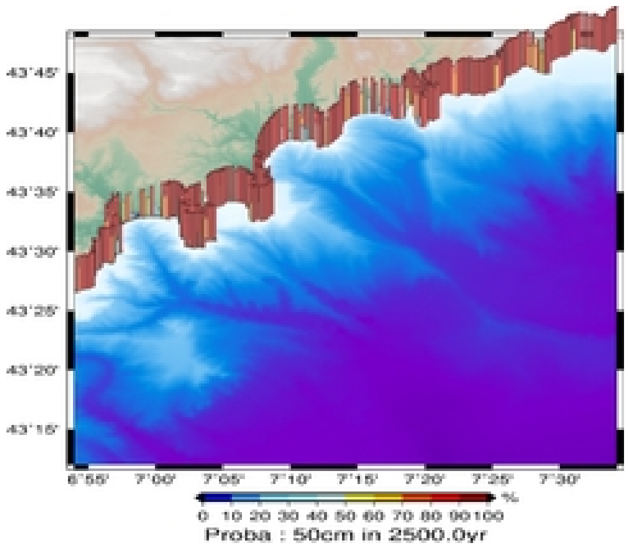
- Stronger maximum waves heights expected in easternmost areas
  - up to 100% probability of 1.2 m waves in the Alpes Maritimes and Var departments
- Lower amplitudes expected toward the west
  - up to 100% probability of 50 cm waves in the Bouches-du-Rhône department
  - up to 80-90% probability of 50 cm waves locally in Hérault, Aude and Py-Orientales

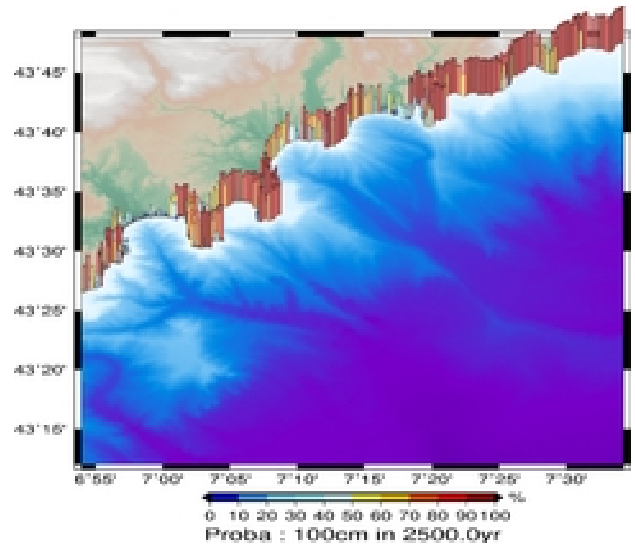
Warning level and Return period

Probabilistic representation of exeeding the advisory (left) and watch (right) alert over 2500 (top) and 10000 yr (bottom)

Alpes Maritimes

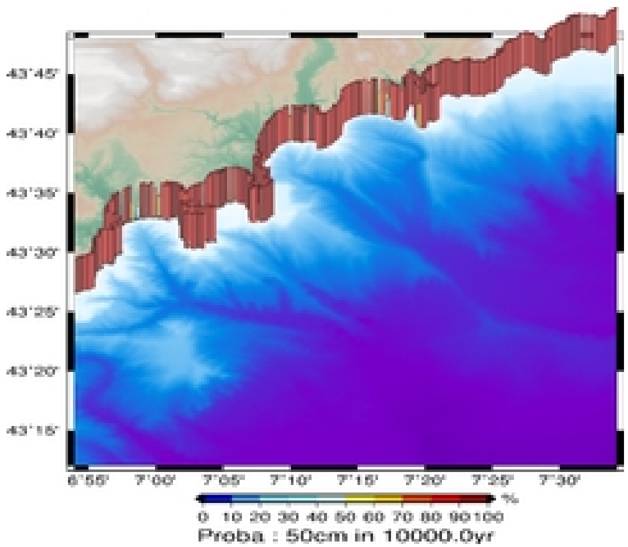
Advisory Probability 2500 yrs

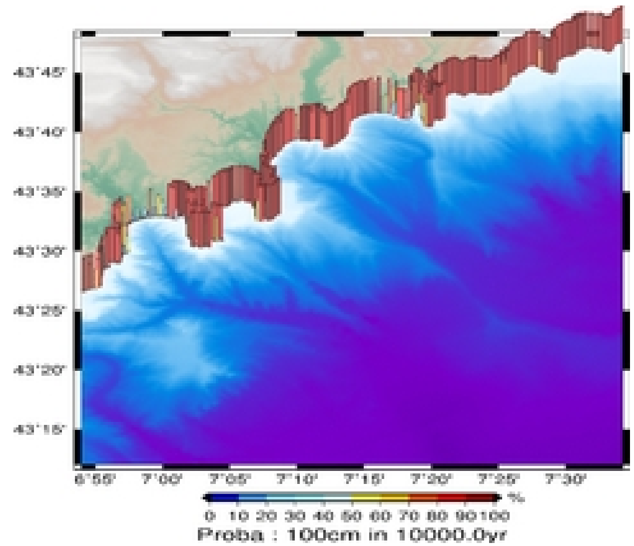




Watch Probability 2500 yrs

Advisory Probability 10000 yrs

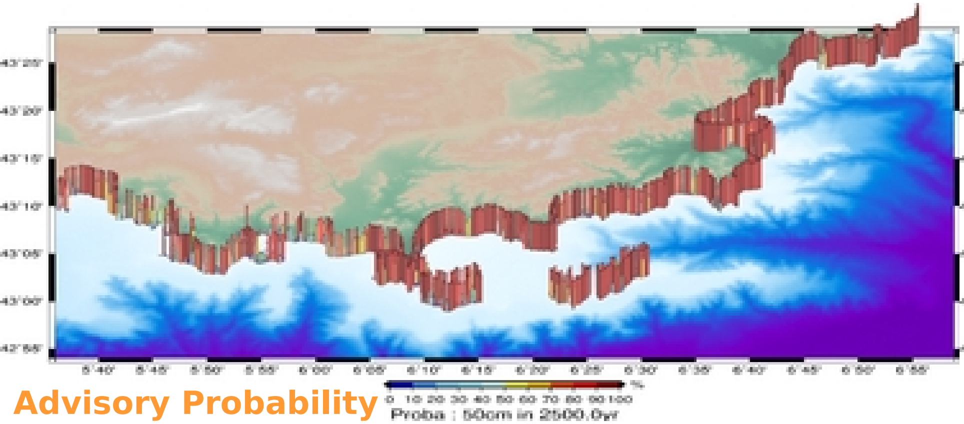




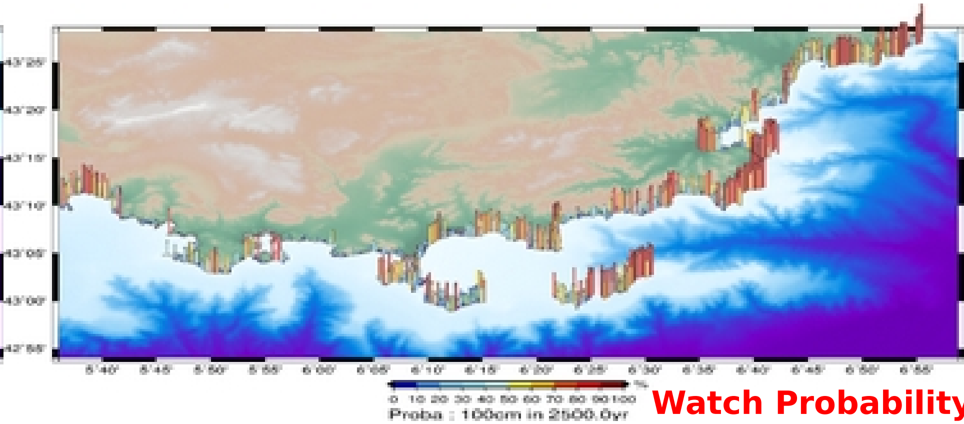
Watch Probability 10000 yrs

Probabilistic representation of exeeding the advisory (left) and watch (right) alert over 2500 (top) and 10000 yr (bottom)

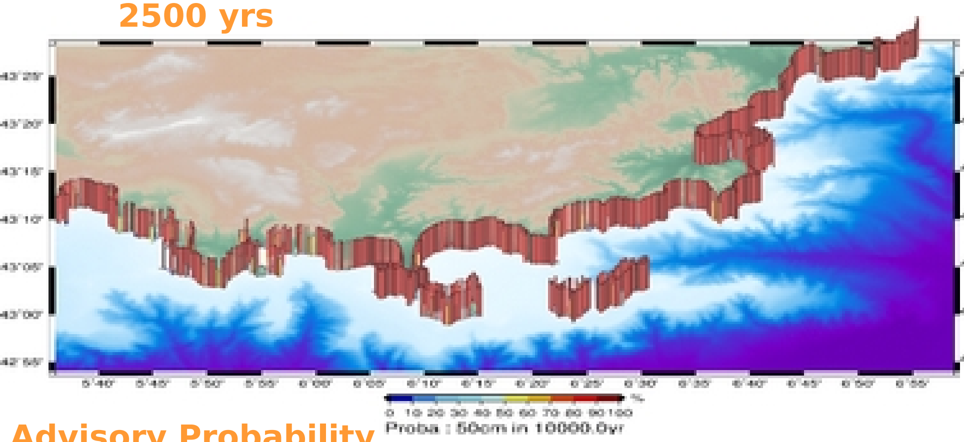
Var



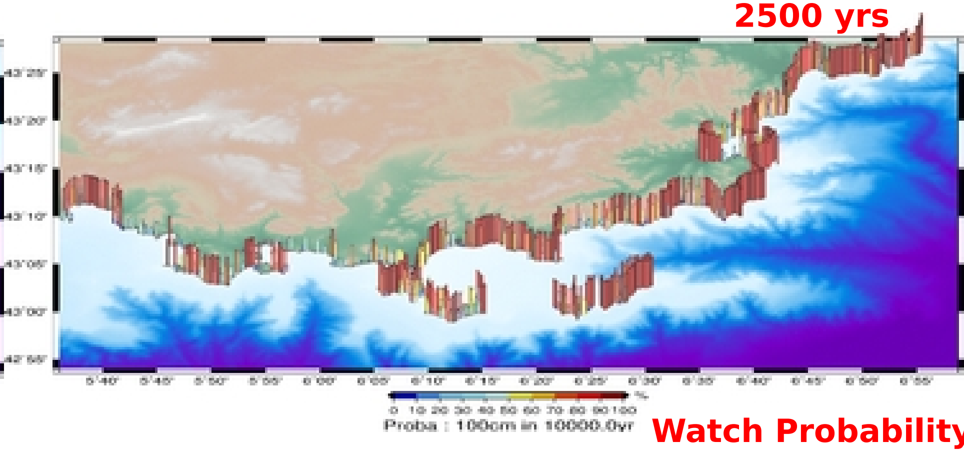
Advisory Probability 2500 yrs



Watch Probability 2500 yrs



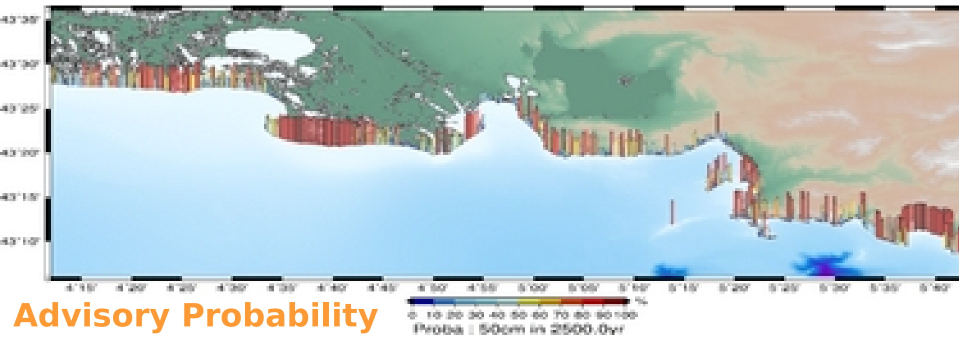
Advisory Probability 10000 yrs



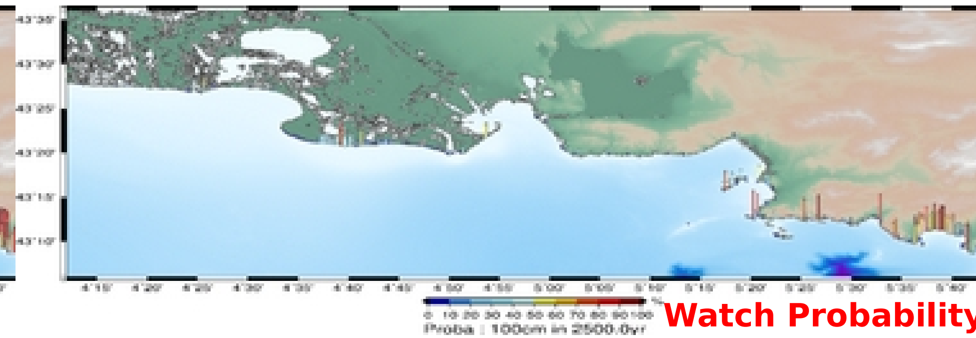
Watch Probability 10000 yrs

Probabilistic representation of exeeding the advisory (left) and watch (right) alert over 2500 (top) and 10000 yr (bottom)

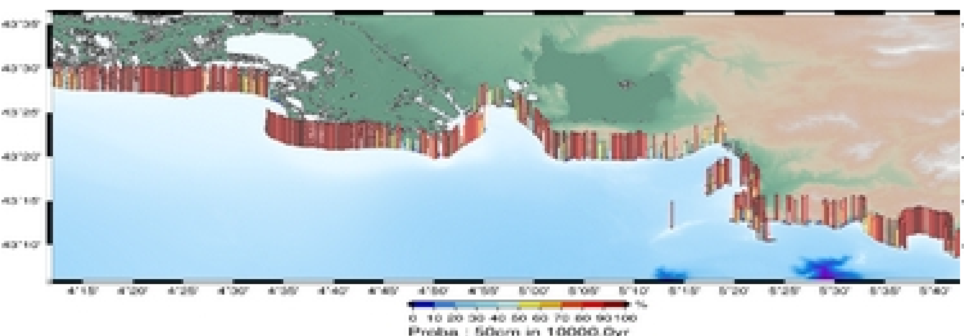
Bouches du Rhône



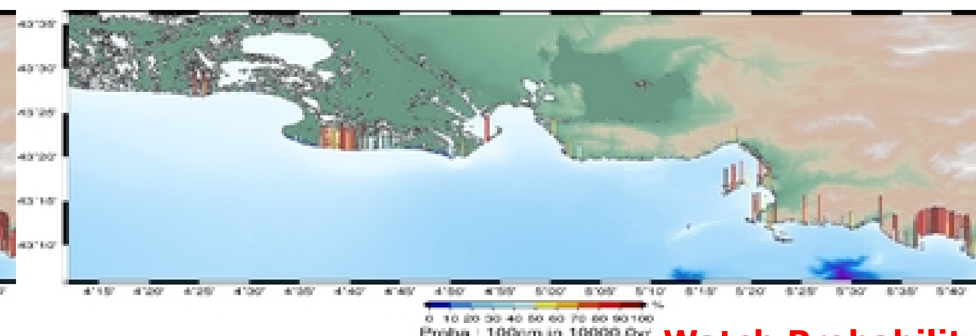
Advisory Probability
2500 yrs



Watch Probability
2500 yrs



Advisory Probability
10000 yrs

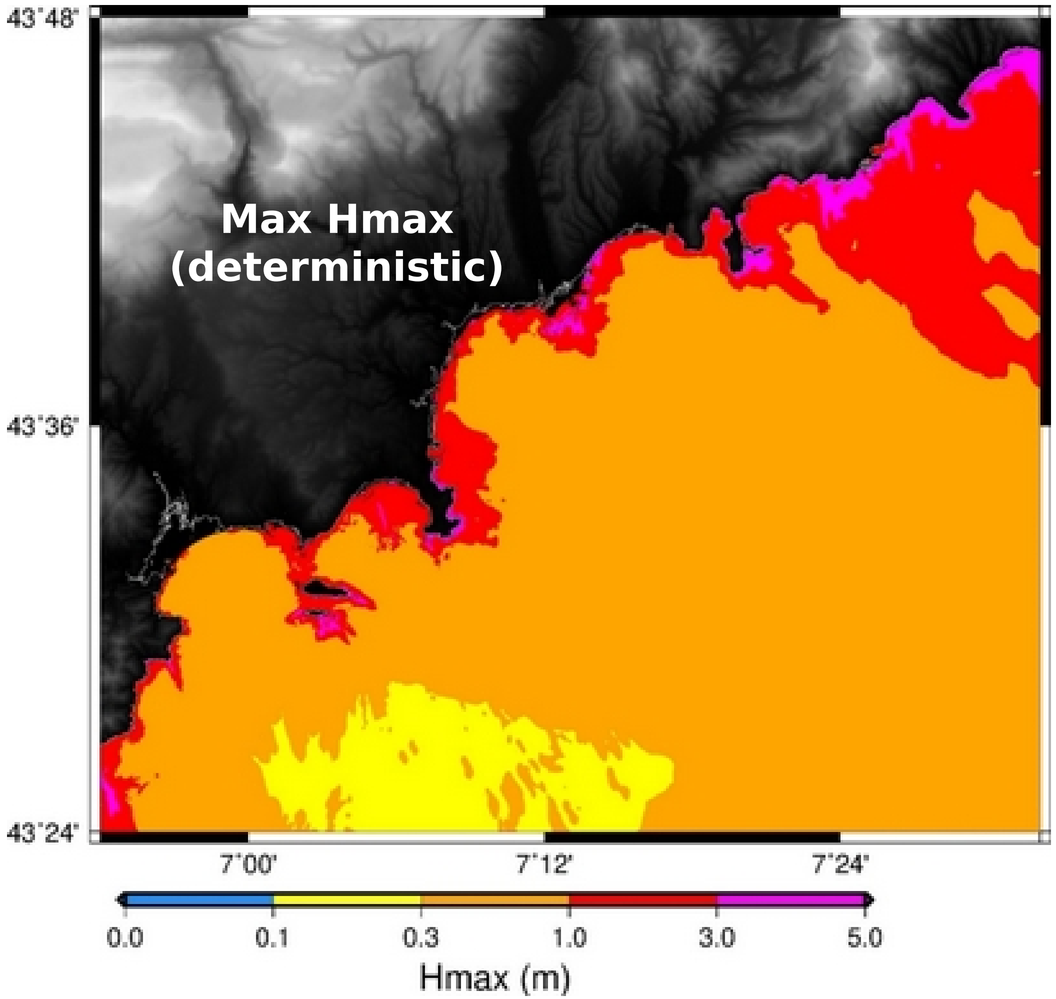


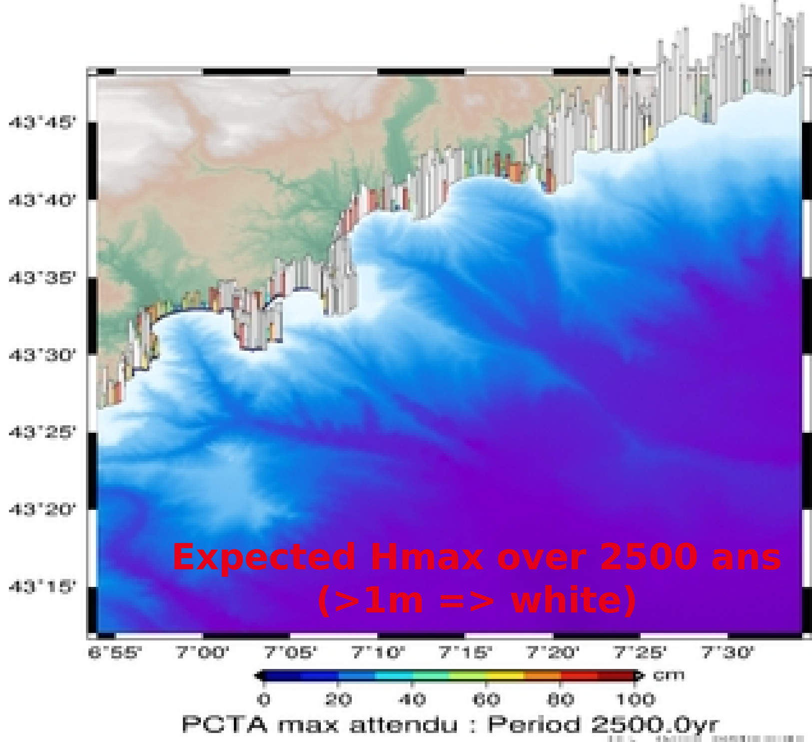
Watch Probability
10000 yrs

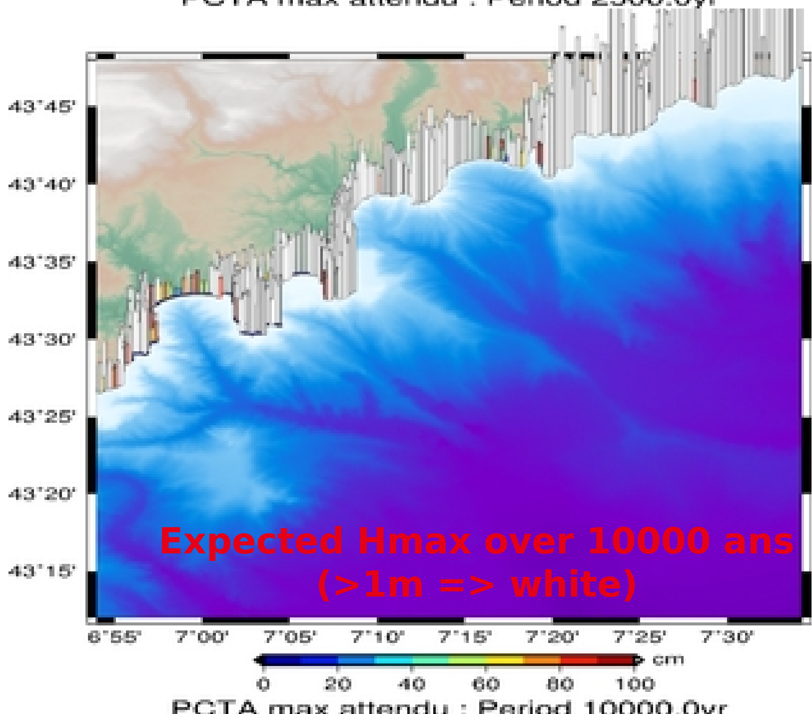
Deterministic vs Probabilistic

Comparison of Deterministic (left) vs Probabilistic representation (right)

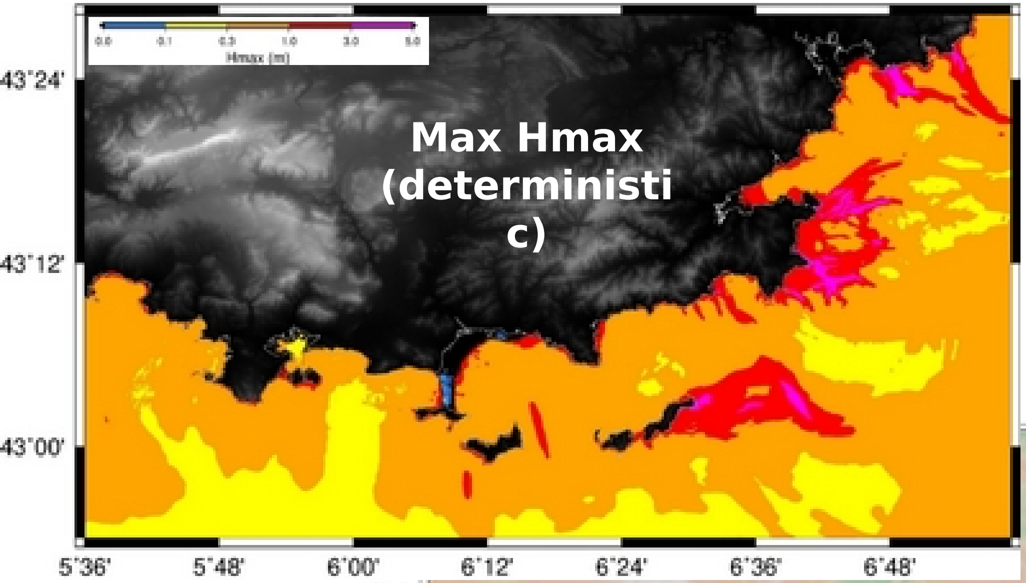
Alpes Maritimes



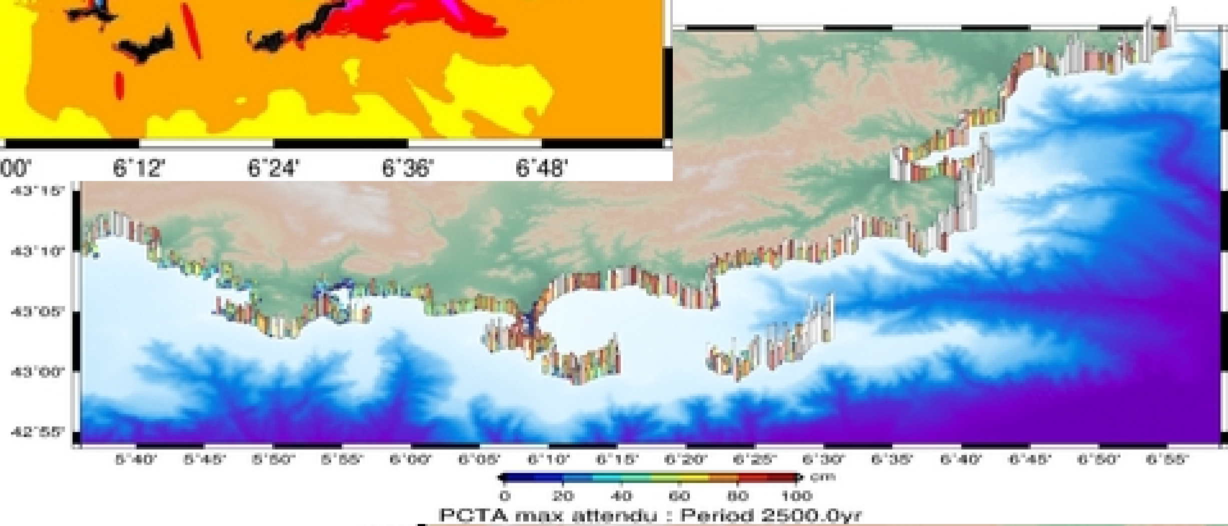




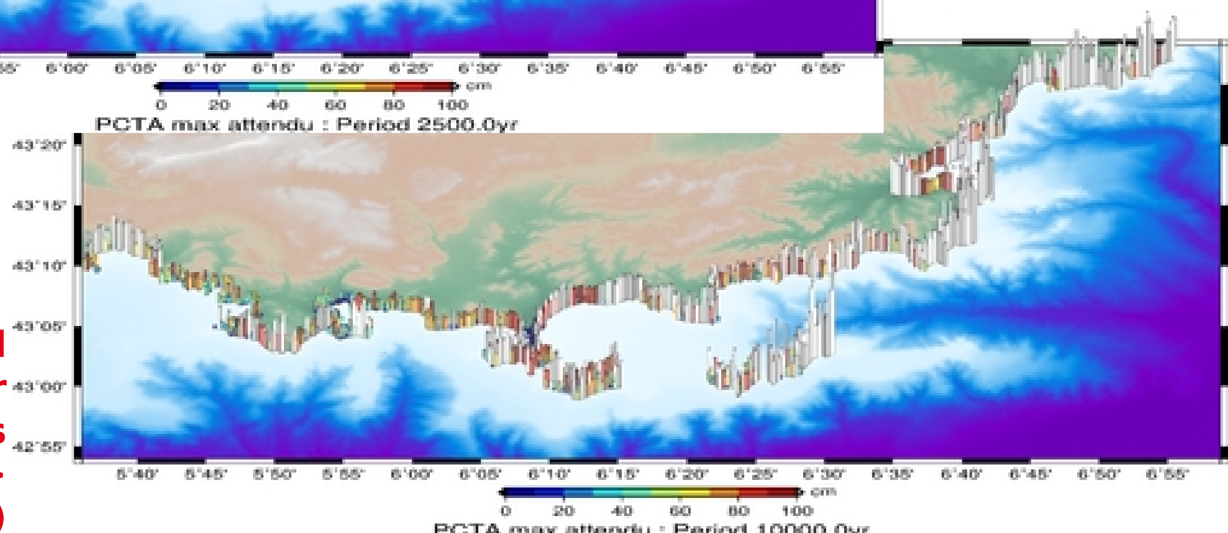
Comparison of Deterministic (top) vs Probabilistic representation



Var



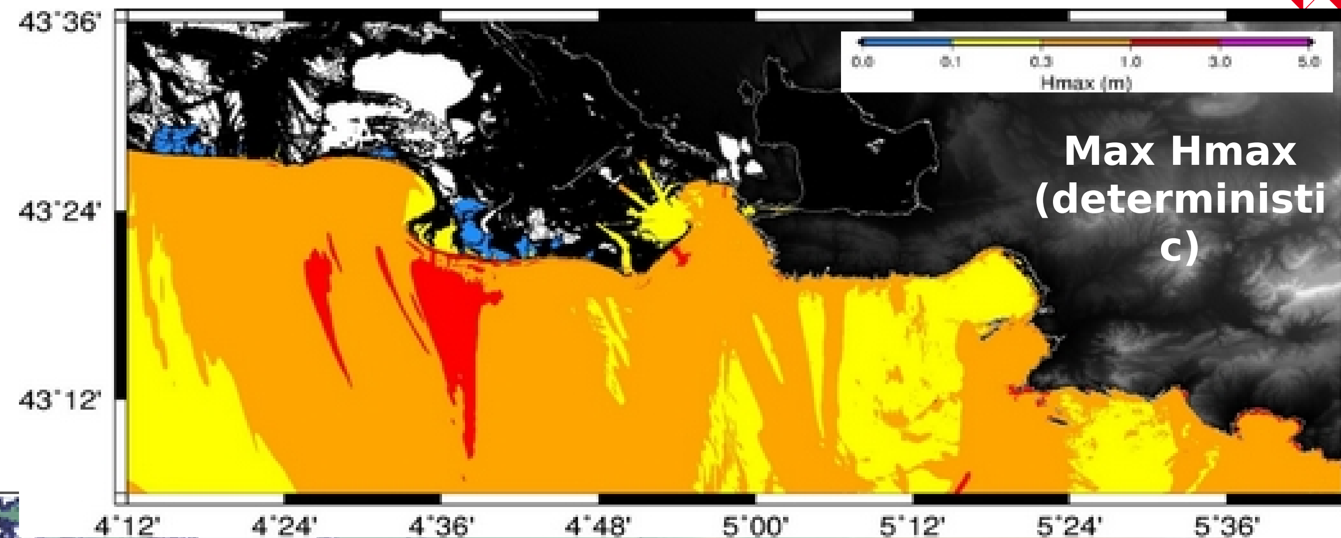
Expected Hmax over 2500 ans (>1m => white)

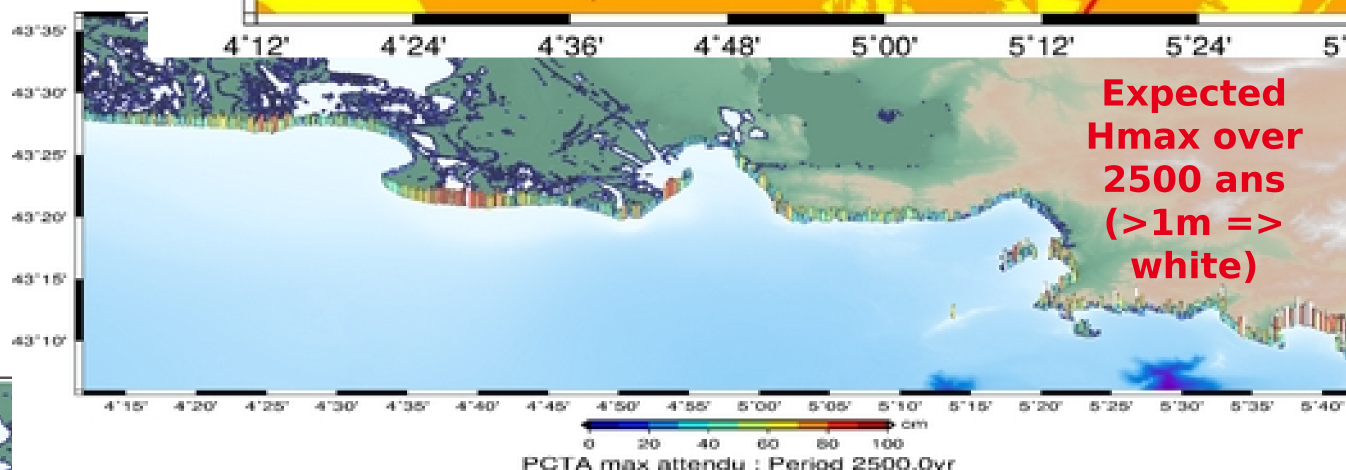


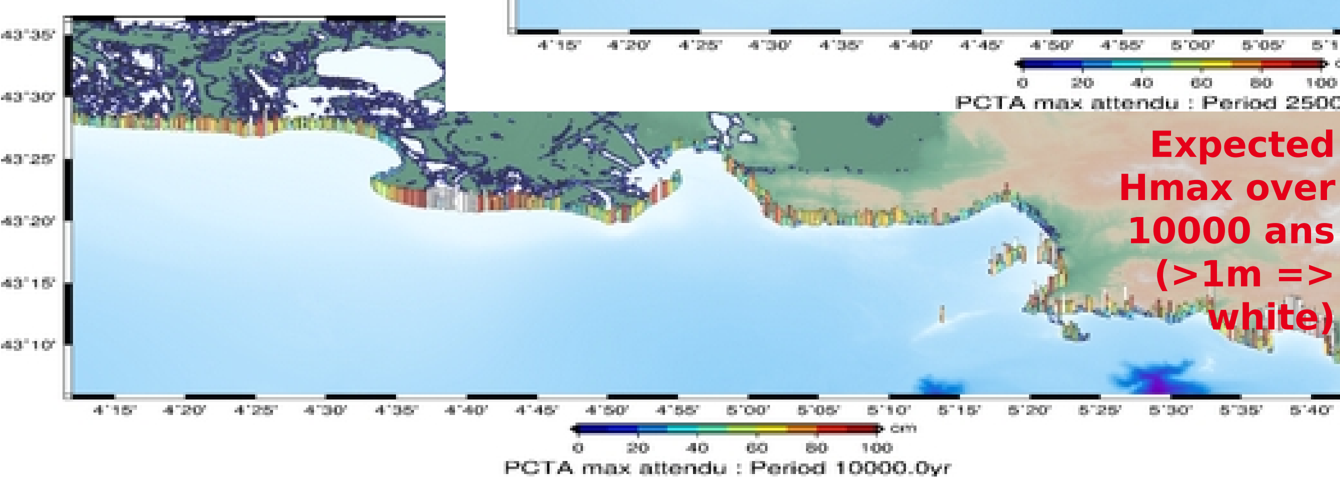
Expected Hmax over 10000 ans (>1m => white)

Comparison of Deterministic (top) vs Probabilistic representation

Bouches du Rhône



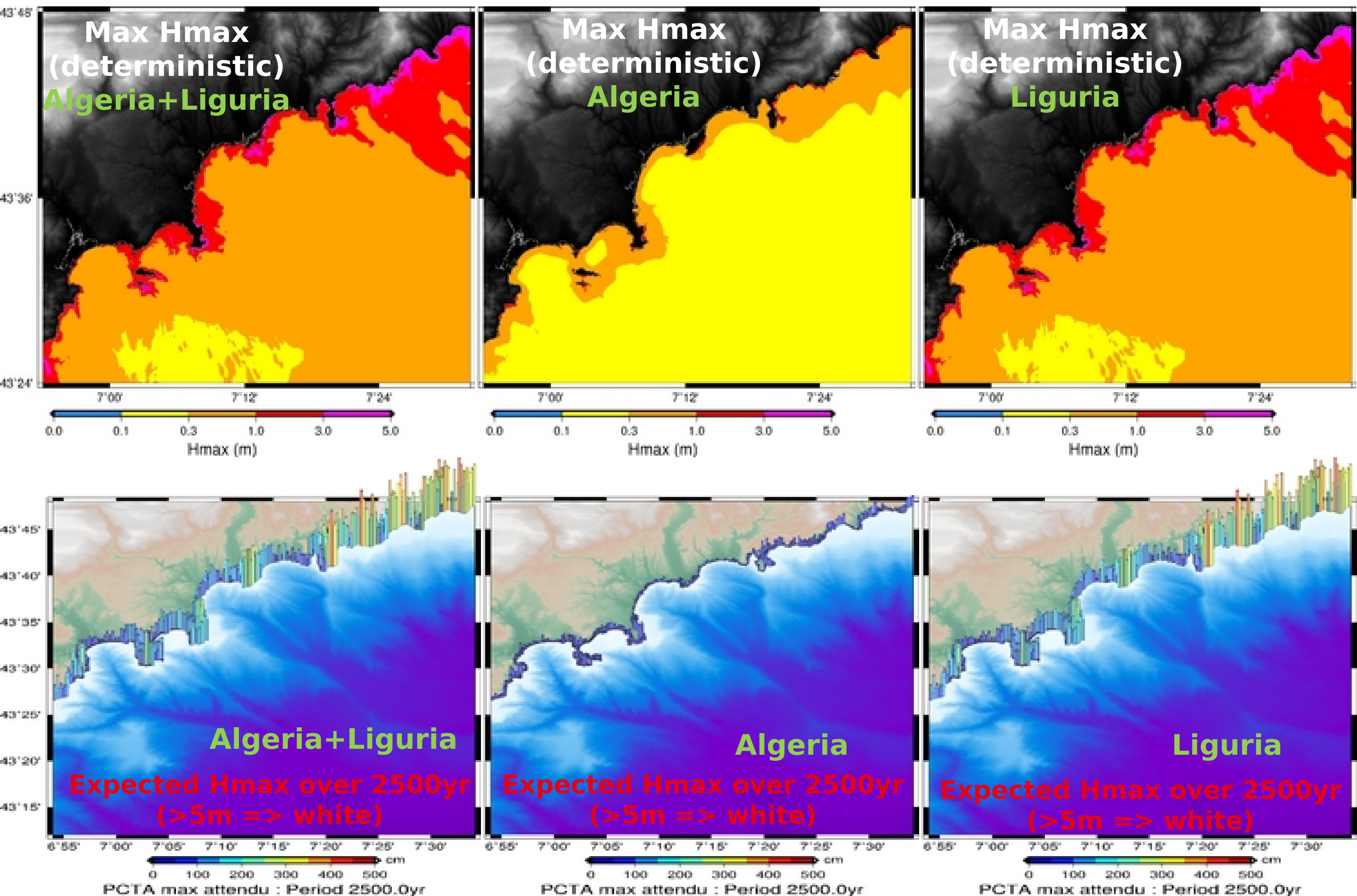




Hazard vs Seismogenic zones

Influence of earthquake location in Deterministic (top) and Probabilistic (bottom) representation

Alpes Maritimes



Conclusion

- High spatial resolution remains a key requirement to accurately capture local amplification effects and inundation zones

- Tsunami modeling codes are able to reproduce observation, but computational time > 45 min (full calculation using nested grids)

  => challenge in near/regional operational context

- Ability to deliver high-resolution coastal tsunami forecasts in near-real time using surrogate models (amplification laws, AI,...), which is essential for timely civil protection decisions

- The integration of advanced modeling techniques and operational constraints contributes to next-generation early warning capabilities

- Put efforts on developing shared operational indicators and geospatial products compatible with civil protection platforms

- Improvement of Tsunami hazard mapping for emergency planning: need to evaluate the amount of deterministic vs probabilistic to include

- Future work : expanding scenario databases, improving uncertainty quantification, and coupling real-time hazard forecasts with impact and vulnerability assessments

  => better support emergency management