DE LA RECHERCHE À L'INDUSTRIE

[EGU2020-5554]

Tsunami hazard associated to earthquakes along the French Mediterranean coastslines

A probabilistic approach (PTHA)

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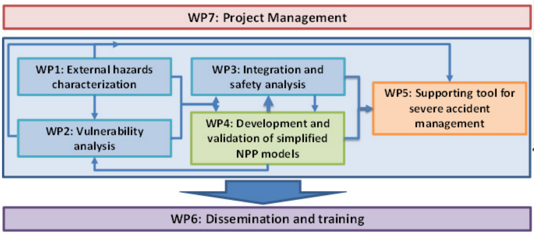
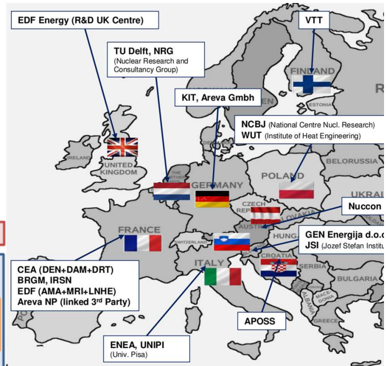
Outline

About N.A.R.S.I.S.

New Approach to Reactor
Safety ImprovementS
2017–2021





www.narsis.eu

The work I will present you is co-founded by Euratom H2020 **NARSIS** project and CEA. NARSIS means New Approach to Reactor Safety ImprovementS. It is an **European** project involving 18 partners in 10 countries. The **main objective** of the project is to improve safety and reliability of Generation II and III reactors. The project includes the characterization of potential physical threats due to different **external hazards** and scenarios (WP1), especially using **probabilistic hazard assessment** for **tsunamis**, extreme weather and flooding and their impacts on facilities and extreme earthquakes effects.

Outline

26 Dec., 2004 Sumatra-Andaman earthquake and tsunami

- Mw9.1 Burma and Indian plates
- 250 000–300 000 dead people
- The deadliest one

11 March, 2011 Tohoku earthquake and tsunami

- Mw9.0 Pacific and Northern Honshu plates
- Low altitude of the Fukushima NPP
- Nuclear accident

Two time scales

- ✔ Warning time scale: starting with the triggering event in real time
- ✔ Historical time scale:
  - Study of past events and extrapolation to future events
    - DTHA: conservative
    - PTHA: determination of the most affected zones, determination of the most threatening zones
  - Evacuation plannification, building engineering

Since the major tsunamigenic earthquakes at Sumatra in December 2004 and Tohoku in March 2011, the determination of the tsunami hazard is questioned **worldwide**.

The Sumatra tsunami is known as the **deadliest** tsunami within living memory (250 000–300 000 dead people). The lack of information and communication is responsible for part of this situation (Okal, 2011).

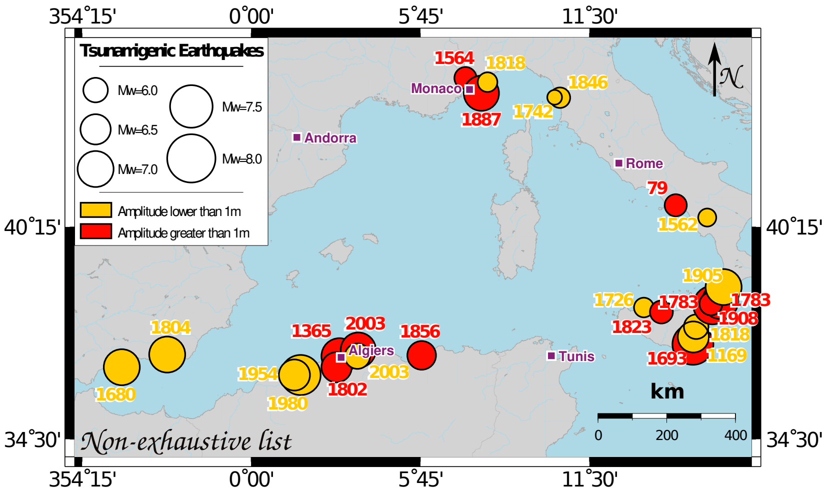
The 2011 Tohoku tsunami caused a great deal of attention, strengthened by the Fukushima Nuclear Power Plant **accident**. The reactors were stopped after the Mw9.0 earthquake, but the elevation of the NPP was **too low in altitude** to be preserved from the tsunami waves that exceeded 10 m-height at the NPP place.

These two high-profile events illustrate the interest to correctly determine the tsunami hazard in order to communicate truthful analyses.

They also illustrate that the tsunami hazard must be studied at **several time scales**:
1) the **warning** time scale, from the triggering event (often an earthquake), and
2) the **historical** time scale.

At historical time scale, we study **past events** to extrapolate to **probable future events**. Two approaches exist:
1) The Deterministic Tsunami Hazard Assesment (**DTHA**) look for the worst probable scenario that can threaten a place.
2) The Probabilistic Tsunami Hazard Assesment (**PTHA**) look for all probable scenarios. A weight is given to each probable scenario in order to get the **probability of exceeding a threshold value in a return period** (i.e. the maximum water elevation).

This study at historical scale is necessary to plan evacuation and design buildings.



Adapted from fig. 1 in Gailler et al. (2013)

Tsunamis in the Western part of the Mediterranean Sea are **not frequent and little destructive** at regional scale (i.e. Western Mediterranean Sea area).

However they exist. This map show most of the earthquakes that triggred tsunamis in this part of the Mediterranean Sea.

Yellow circles show earthquakes that generated less than 1m water elevation along the Western Mediterranean coastlines. **Red** circles show earthquakes that triggered tsunamis with waves locally **upper than 1m**.

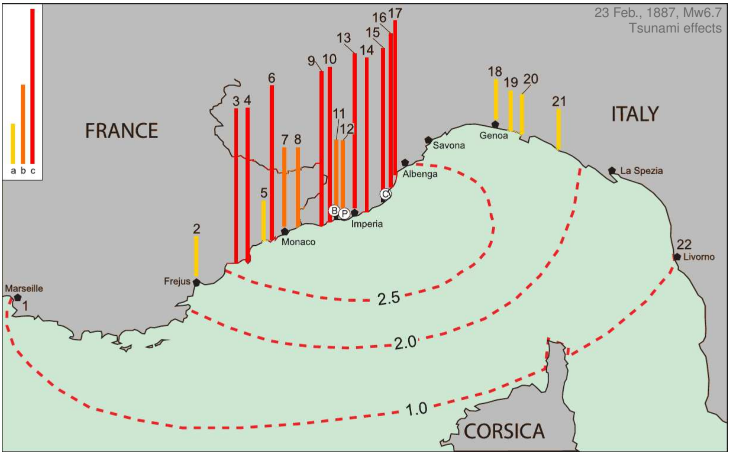
Especially, the **Mw6.7 earthquake**, that occured offshore in front of Imperia in 1887, impacted a lot the coastlines along the **Ligurian Sea**.

The red dashed lines, on the map show the intensity distribution of the tsunami that was generated by the Mw6.7 earthquake.
The vertical lines show the wave heights that were observed in some cities along the coastlines.

Notably, waves have reached **heigths between** 1 m **and** 2 m at Cannes [3] and Antibes [4] cities.

The question of what is the risk naturally arises.

Here we focus on the characterization of the **tsunami hazard** that is a part of the risk.



hmax: $0 < a < 0.5\,\mathrm{m}$ $0.5 < b < 1\,\mathrm{m}$ $1 < c < 2\,\mathrm{m}$

Locations: 1, Marseille; 2, Fréjus; 3, Cannes; 4, Antibes;5, Nice; 6, St Jean-Cap-Ferrat; 7, Monaco; 8, Menton; 9, Ospedaletti; 10, San Remo; 11, Arma di Taggia; 12, Riva Ligure; 13, Imperia; 14, Oneglia; 15, Diano Marina; 16, Andora; 17, Alassio; 18, Genoa; 19, Bogliasco; 20, Recco; 21, Sestri Levante; 22, Livorno.
Dotted red lines: distribution of the intensity of the tsunami [intensity scale from Sieberg (1923) modified by Ambraseys (1962), compilation by A. Laurenti].

What's next?

Adapted from fig 5 from Larroque et al. (2012)

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Sørensen et al. (2012)

- ✔ Tsunami hazard, due to earthquakes, in the Mediterranean Sea using PTHA
- ✔ Long-wave offshore to get peak offshore tsunami amplitudes
- ✔ Extrapolation to PCTAs using Green's law
- ✔ Contribution to tsunami hazard per seismogenic zone

TSUMAPS-NEAM

- ✔ European project
- ✔ Tsunami hazard along European coastlines
- ✔ Peak offshore tsunami amplitude extrapolated to PCTAs using Green's law

TANDEM

- ✔ French project
- ✔ Tsunami hazard along French coastlines (North Atlantic Ocean and French Channel)
- ✔ DTHA using high-resolution simulations

- ✘ Green's law approximation are not accurate nearshore
- ✘ DTHA only look at the worst probable scenario

Several studies had the aim to study the tsunami hazard along the European coastlines. Among other, we can cite

1. The study of Sørensen et al. (2012)
2. TSUMAP-NEAM project
3. TANDEM project.

Sørensen et al. (2012) quantified the tsunami hazard in the *Mediterranean Sea* using **PTHA**. They simulated tsunamis using **long-wave model** to get the **peak offshore tsunami amplitude** and extrapolated it to Peak Coastal Tsunami Amplitude (**PCTA**) using Green's law (Green, 1838) taken at low depth, generally around 1 m depth (e.g. Glimsdal et al., 2019; Selva et al., 2016).

TSUMAPS-NEAM was a **European project** with the objective to evaluate the tsunami hazard along the *European coastlines* (TSUMAPS-NEAM, 2020). In this project, peaks offshore amplitudes were also **extrapolated to PCTAs**, also using Green's law.

One of the objectives of the French project TANDEM was to estimate the tsunami hazard along the **French coastlines**, especially in the *North Eastern Atlantic Ocean and in the French Channel* (TANDEM). **DTHA** was used on **high resolution** grids.

However PCTAs obtained from Green's law approximations provide a **crude approximation** of wave heights at the coast only, within a factor of 2 at best (e.g. Gailler et al., 2018).
Also if the results from TANDEM project are **more accurate**, they only consider the **worst probable** scenario. **However, smaller events can be significant, especially since they are more frequent.**

Introduction
Finding and response

- ✔ Few historical tsunamis along the French Mediterranean coastlines
- ✔ Few earthquakes can potentially generate a significant tsunami along the French Mediterranean coastlines on a human scale
- ✘ Large coastal populations: Cannes, Nice, Marseille...
- ✘ non-optimal adaptation of equipment

➜ Evaluation of the hazard down to the coastal level for large return times

- ✘ Deterministic analysis: a large but far earthquake might generate lower water height along the French coastlines than a small and close earthquake
- ✓ Probabilistic Tsunami Hazard Assessement (PTHA)

We foccuse on the tsunami hazard along the **French Mediterranean coastlines** that is due to **earthquakes**.

There are **few historical tsunamis** and **few earthquakes** can potentially generate a significant tsunami along the French Mediterranean coastlines on **a human scale**.

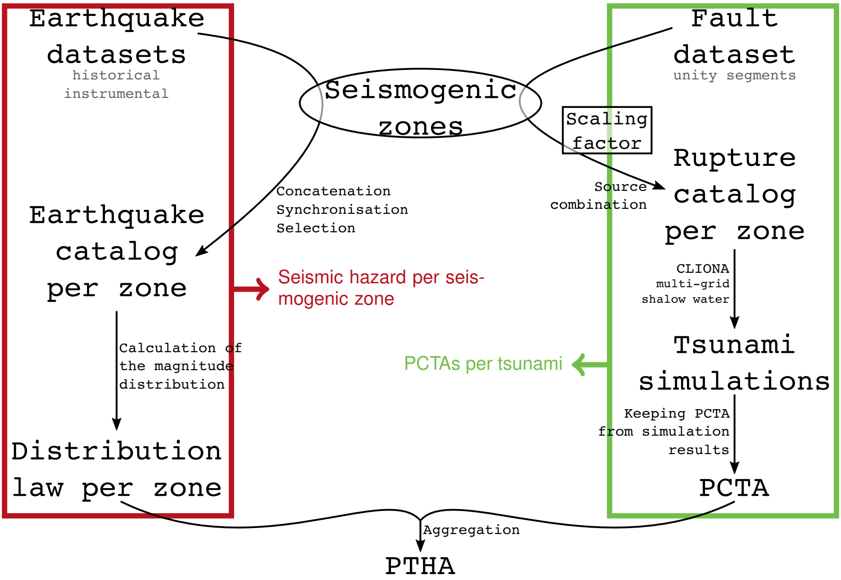
This is a great thing but it can also become a danger because there are **large coastal populations**, such as in Cannes, Nice, especially during **summer holidays**, that are not aware of the danger. Moreover there are **few adaptations of equipments**.

It is then necessary to determine the tsunami hazard along the French Mediterranean coastlines **down to the coastal level** (beaches, harbours).

A **DTHA** approach is **not the most adapted** due to the few occurence of great events.

We then use Probabilistic Tsunami Hazard Assessment to evaluate the hazard along the French Mediterranean coastlines down to coastal level.

Outline



Here is an **overview** of the method we use to determine tsunami hazard, due to earthquakes, along the French Mediterranean coastlines.

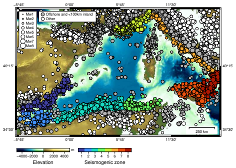
On the left side, we determine the **seismic hazard**, from the collect of the data to the **distribution law** of the magnitude.
This is necessary as the **probability** of having a tsunami with a given **intensity** is directly linked to the **probability of the earthquake** that can triggered that tsunami.

On the right side, we determine all the **probable scenarios** of rupture that can trigger a tsunami and **simulate** these scenarios to get the **PCTAs** down to the **coastal level**.

Whether for seismic hazard or for tsunamis scenarios, we work by **seismogenic zone** (more details are given here after).

The distribution law of the magnitude and the PCTAs are then combined to process the PTHA.

Catalogue of reference



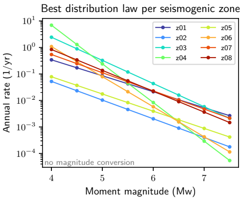
- ✔ Synchronization of several datasets*
  - ❑ Completeness, Magnitude conversion?
- ✔ Seismogenic zones (Sørensen et al., 2012)
  - ❑ Accuracy, Missing zones?

* CMT, EMEC, FCAT-17, ISC, NOAA, SHARE, USGS

Seismogenic zones†	
z01	Southeastern Spain
z02	Nothern Morocco
z03	Northern Algeria
z04	Northern Tunisia
z05	Ligurian Coast
z06	Western Italy
z07	Sicily
z08	Calabria

† Sørensen et al. (2012)

Distribution law (Gutenberg-Richter)



- ✔ Magnitude of completeness
  - ❑ Method, Parameters?
- ✔ Distribution law
  - ❑ Weichert's method: parameters? (Weichert, 1980)

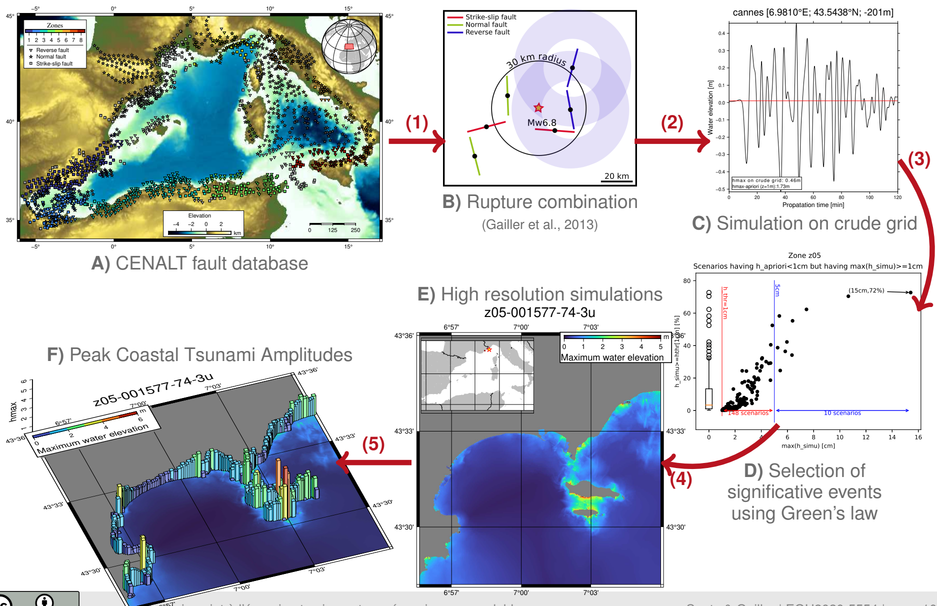
The seismic hazard is the **foundation** of the PTHA and thus need to be **carefully** determined. Indeed an inaccurate catalog will lead to inaccurate determination of the probabilities of PCTA.

We need to **synchronize various databasets** of earthquakes because some have **historical** earthquakes but stop more than 10 years ago (FCAT-17, SHARE) and others are dayly updated but have only **instrumental** records (USGS, EMEC,...). Morever all does not span worldwilde.
Despite the synchronisation of the various databases, we need to be careful of the **completeness** of the synchronized catalogue (time, magnitude and space).

The occurrence of earthquakes depends on the **seismotectonic context**; i.e. the Sicily region triggers more earthquakes and stronger earthquakes than the Ligurian region.
Then, we split the main earthquake catalogue into **sub-catalogues depending on seismogenic zones** in order to determine an accurate and consistent annual rate of a moment magnitude in each seismogenic zone.
These seismogenic zones must be determined **consistently** with the **seismic rate** and the **faulting regime** of each zone.
We use the seismogenic zones proposed in Sørensen et al. (2012).
The accuracy of these zone has to be **questionned**.
Also some areas have earthquakes but are not part of a seismogenic zone, yet.

We assume here that the magnitude of the earthquakes within each zone follow a **Gutenberg-Richeter law**.
The law is determine using **Weichert's method** (Weichert, 1980), based on the **maximum likehood** between a model and the data.
The method includes **seismic rates for periods of time** (period of completeness) that **depend on magnitude**.

Method
Tsunamis



(A) We use the **fault database** of the French Tsunami Warning Center (CENALT) to build a **catalogue of ruptures**. The fault database consists in a **unit source function system** which follow the **major structural trends** of the Western Mediterranean basin seismogenic context (Gailler et al., 2013).

(B) We **combine** unit sources to build a **rupture** (20 km wide, 25 km length, 1 m slip, Gailler et al. (2013)).
Lengths and widths of combined unit sources follow **Wells and Coppersmith (1994) laws** (fixing L = 200 km for M_w = 8.0) and the **slip is scaled by a factor** F_s in order to **fit** the moment magnitude M_w.
The combination is controlled geometrically by the distance between two unit sources and the azimuth difference between these two sources. The distance between two faults is set between 18.5 km and 37.5 km and the azimuth difference is set lower than 40°.
The available combinations of unit source in a seismogenic zone give the **maximum moment magnitude** in the zone.

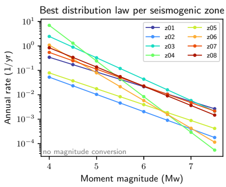
(C) A first tsunami simulation of each rupture is done in a **crude grid** in order to collect **Peak Offshore Tsunami Amplitde** (POTA) where the water depth is ∼100 m (CLIONA code, CEA). We then use the **Green's law** (Green, 1838) to extrapolate each POTA to an *a priori* PCTA $\text{hmax}_{\text{apriori}}$ (PCTA).

(D) We then select all rupture for which $\text{hmax}_{\text{apriori}}$ is greater than or equal to 1 cm. This reduces the number of high-resolution simulation to do, and thus **reduces the computational time**. This method of selection was configure using high-resolution simulations, on Cannes area, of all ruptures in the Ligurian zone (z05), for magnitudes between 5.5 and 7.4.

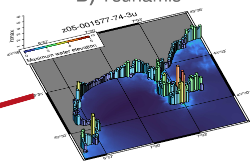
(E) We run CLIONA code (CEA, e.g. A.Poupardin et al., 2018) using **shallow water** equations and **nested-grid** resolution down to the coastal level (10 m) for each rupture selected in (D). The length of the simulation is adapted for each seismogenic zone, here again to reduce the computational time.

(F) Last step, here consists in **collecting the PCTAs**. The resultant files are smaller and easier to use than grids.

A) Seismic hazard



B) Tsunamis



C) Probability of occurence of a rupture scenario

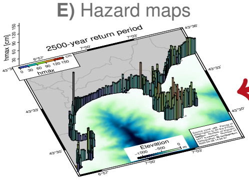
$$P_i = \frac{\lambda\left(M_{w_i}\right)}{N_{\text{scenario}}\left(M_{w_i}\right)}$$

D) Probability of exceedance of a PCTA at a site of referecence

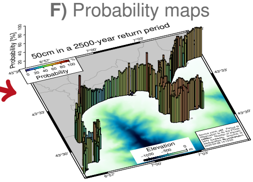
$$P\left((x,y)_{\text{ref}}, \text{PCTA}_{\text{ref}}\right) = \sum_i P_i\left((x,y)_{\text{ref}}, \text{PCTA} \geq \text{PCTA}_{\text{ref}}\right)$$

PTHA

E) Hazard maps



F) Probability maps



(C) The **annual probability** P of each scenario i, during the period T, is given by the ***(A)*** **annual rate of its moment magnitude** M_w which is determined from the distribution law and by the ***(B)*** **number of probable scenarios** that can generate an earthquake of magnitude M_w.

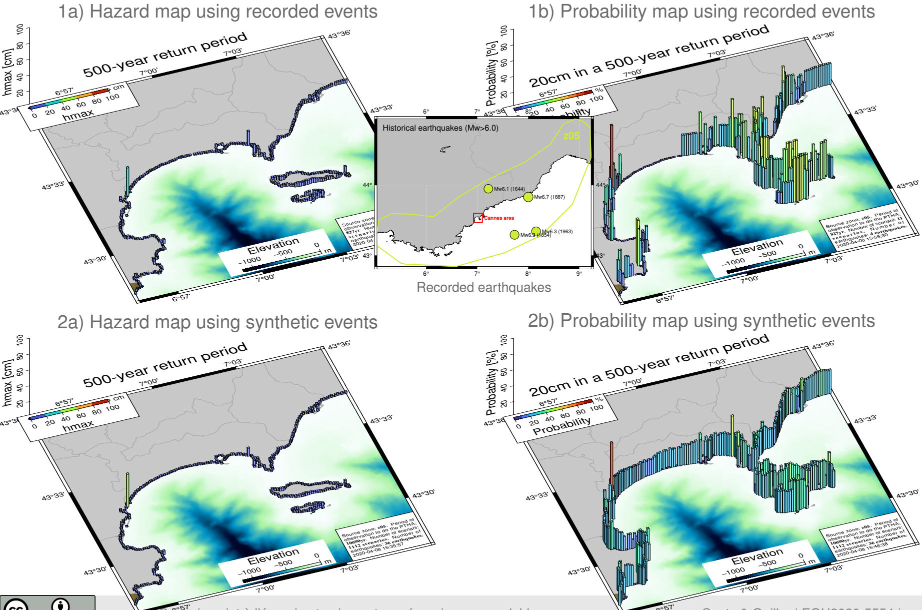
The annual probability of each PCTA is equal to the annual probability of its rupture scenario.

(D) The **annual probability of exceeding a PCTA**, at each place, is computed by **aggregation** of any rupture scenario that can exceed a given PCTA, such that the annual probability is the **sum of the annual probability** of each rupture scenario triggering a tsunami that exceeds the chosen PCTA at the chosen place.

We can use these annual rates and this probabilities to plot ***(E)*** **hazard maps**, which give the maximum water elevation in a return period, or to plot ***(F)*** **probability maps**, which show the probability of experiment a water elevation during a return pediod. **Probability curves** can also be given.

Outline

Results: Tsunamis impacting Cannes area (z05)
Extension of the period of observation



We now present some results of the PTHA along the coastlines in Cannes city area.

Earthquakes sources are located in the Ligurian Sea (z05). High-resolution simulations from other seismogenic zones are not finished yet.

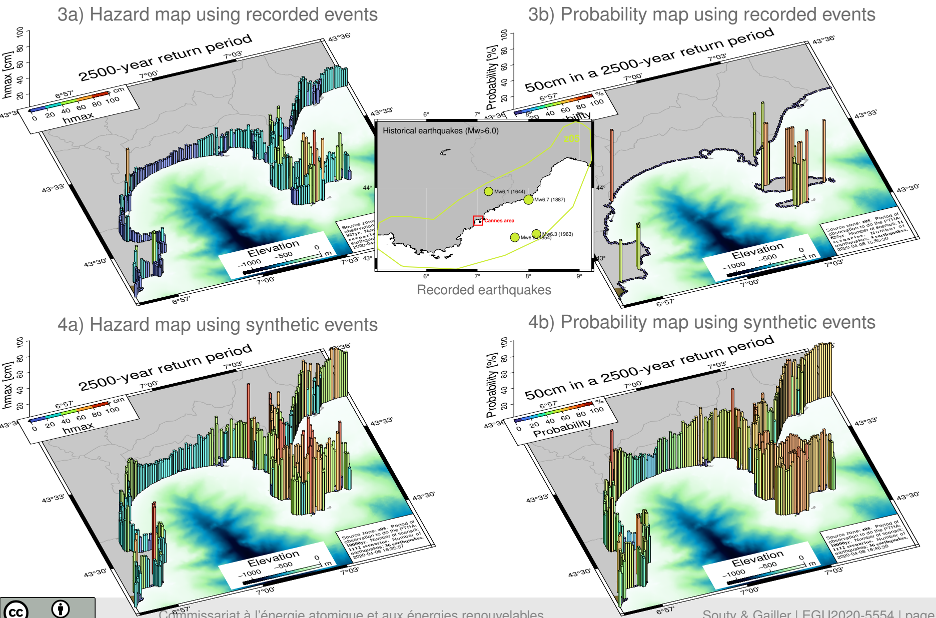
> The **hazard maps** for a 500yr return period are shown on the *left side*, and the probability to experiment at least 1 tsunamic wave having *hmax* $\geq$ 20 cm in a 500yr return period on the **probability maps** on the *right side*.
> *At the top*, results are given using only the 4 earthquakes, with $M_w \geq 6.0$, recorded in the **real period of observation** of 827yr. The 4 earthquakes are shown in the *centered map*.
> *At the bottom*, results are given for the 36 earthquakes of $Mw \geq 6.0$ that can occur during an **extended period of observation** of 10 000yr. This number of earthquakes is obtained using the **distribution law** (MBS+Weichert, dM0.2, dy1).
> 11 scenarios correspond to the 4 recorded earthquakes, 1112 scenarios can generate earthquakes of $M_w \geq 6.0$ in the Ligurian Sea seismogenic zone.

Looking at the hazard maps, we observe that the maximum water elevation is **quite similar** whether we choose to use the ***(1a)*** real period of observation or the ***(2a)*** extended period of observation. However, the probability of experiment at least one wave height equal to or greater than 20 cm in a 500yr return period is different whether we choose to use the ***(1b)*** real period of observation or the ***(2b)*** extended period of observation.

Indeed the extension of the period of observation allows the model to take into account much more probable scenarios.

This first result illustrates that hazard maps are not self-suficiant to describe the tsunami hazard.

Results: Tsunamis impacting Cannes area (z05)
Extension of the period of observation



We now increase the length of the return time of the analysis from 500yr to 2500yr.

The **hazard maps** for a 2500yr return period are shown on the *left side*, and the probability to experiment at least 1 tsunamic wave having *hmax* $\geq$ 50 cm in a 2500yr return period on the **probability maps** on the *right side*.
At the top, results are given using only the 4 earthquakes, with $M_w \geq 6.0$, recorded in the **real period of observation** of 827yr. The 4 earthquakes are shown in the *centered map*.
At the bottom, results are given for the 36 earthquakes of $Mw \geq 6.0$ that can occur during an **extended period of observation** of 10 000yr. This number of earthquakes is obtained using the **distribution law** (MBS+Weichert, dM0.2, dy1).
11 scenarios correspond to the 4 recorded earthquakes, 1112 scenarios can generate earthquakes of $M_w \geq 6.0$ in the Ligurian Sea seismogenic zone.

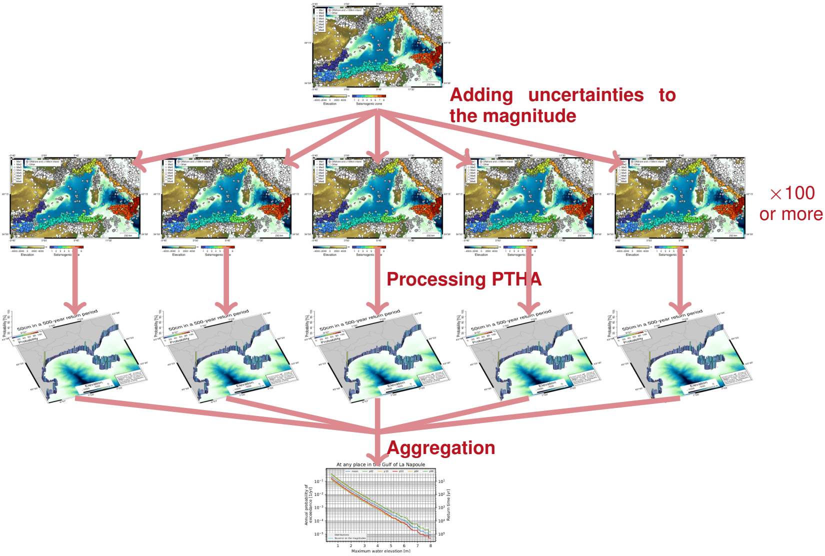
Here the hazard maps are **different** whether we are looking at ***(3a)*** real period of observation or ***(4a)*** the extended period of observation.
Indeed, the **return time is now greater than the period of observation**. It is then a **non-sens** to look at the results from the real period of observation.
The maximum water elevation is here **biased** because the same 11 scenarios are repeated here to reach the 2500yr return period instead of **creating earthquakes elsewhere** in the seismogenic zone.

This also leads to inconsistent probabilities. Indeed according to the ***(3b)*** probability map, there is **almost no-probability** to experiment a 50 cm in a 2500yr when considering only the recorded earhtquakes.
Yet, when we look at the ***(4b)*** probability map when using the extended period of observation, the probabiliy to experiment a 50 cm in a 2500yr is **rarely lower than** 30 %.

The bias induded by the period of observation can have a great impact on the PTHA and thus on civil and building engineering.

It is then necessary to enlarge the period of observation using distribution laws.

Results: Tsunamis impacting Cannes area (z05)
A first overview of the magnitude uncertainties



We want to look at the sensibility of the model due to the uncertainty on magnitudes.

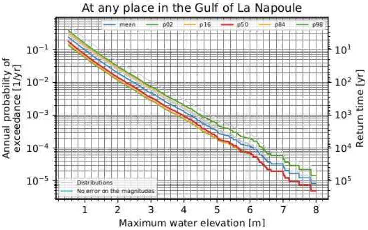
We then duplicate, let's say 100 times, the catalogue of reference and add an uncertainty on the magnitude of each record.
The uncertainty is added following a normal law where the mean is the recorded magnitude and the standard deviation is the error on the magnitude. Here we have choosen a 0.2 uncertainty.

We then process the PTHA for each duplicated catalogue as described in the method section.

Finally, we aggregate the results.

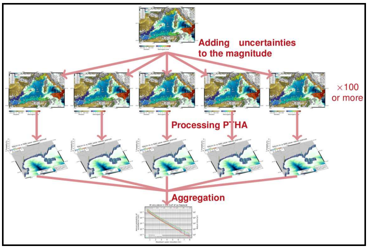
In this example we choose to show the results as hazard curves.

Aggregation



Case	Annual probability (%)	Probability of experiment[1] (%)
Reference	5.72	94.74
Mean	9.65	99.37
2nd percentile	5.72	94.74
16th percentile	5.94	95.32
Median	6.98	97.32
84th percentile	13.60	99.93
98th percentile	15.40	99.98

[1] Probability of experiment at least one wave tsunami equal to or greater than 1 m in a 50-year return period.



- ✔ Annual probability of exceedance of a maximum water elevation at any place along the coastline
- ➠ Work in progress...
- ➠ Annual probability of exceedance of a maximum water elevation at a chosen place along the coastline

At the top left, the curves in the show the **annual probability of exceedance** of a PCTA at **any place** along the coastlines of the studied area.

Each grey curve show the results from 1 duplicated catalogue.
The cyan curve show the results from the catalogue of reference.
The blue and red curves show the mean and mediane hazard curves, respectively, from all the duplicated catalogues and the catatalogue of reference.

The median curve show that the probability to experiment a 1 m PCTA anywhere in the Gulf of La Napoule (Cannes city area) in a 50-year return period is ∼97.32 %[1] (annual probability of∼6.98 %). In the present case, it increases the probability in regards of the probability we would have using only the catalogue of reference (∼94.74 %, annual probability of∼5.72 %).

This work is still **in progress**, but a particular place could have been chosen to study the sensibility due to uncertainties on the magnitudes.

Sensibility analyses can also be done on other parameters during the PTHA process. Such as the choice of the method to determine the distribution laws.

[1] $P = 1 - (1 - p_{\text{annual}})^T$

Outline

Conclusions

Current results: Tsunami-earthquakes from Ligurian Sea impacting Cannes area

- ✓ Needs of synthetic catalog to improve the analysis
- ✓ Probability of experiment a 1 m PCTA anywhere in the Gulf of La Napoule in a 50-year return period
  - ❏ ∼94.7 % when considering no uncertainty on the magnitude
  - ❏ ∼97.3 % when considering uncertainties on the magnitude (median curve)
- ➟ Simulations in progress

Challenges

- ❏ Large amount of data to manage Earthquake entries, Results of the tsunami, Aggregation of the results
- ❏ Many uncertainties to take into accounts at different steps of the analysis Earthquake parameters, Distribution law, Rupture scenarios, Tsunami simulations
- ❏ High number of high-resolution simulations: long computational time

Our answers

- ❏ Semi-automatic processing with structured data hierarchy (➟ work in progress)
- ❏ Sensibility analysis (➟ work in progress)
- ❏ Reduction of the number of the high-resolution simulations using Green's law on low-resolution simulations ($hmax_{apriori}$)

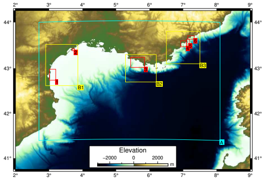
Perspectives

PTHA

- Highlighting the areas that can be the most affected at the level of a municipality
- Tracking the most threatening areas (deaggregation)

Other high-resolution maps (10 m)

- Antibes [5]
- Bandol [3]
- Leucate [1]
- Nice [6]
- Sete [2]



Application to the North Atlantic French coastlines

- Increase of the quantity of data
- Increase of the time of propagation to simulate
- Increase of the number of simulations

DE LA RECHERCHE À L'INDUSTRIE

[EGU2020-5554]

Thank you for your attention.

6 May, 2020

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