Tsunamis: Knowing them to forecast them better

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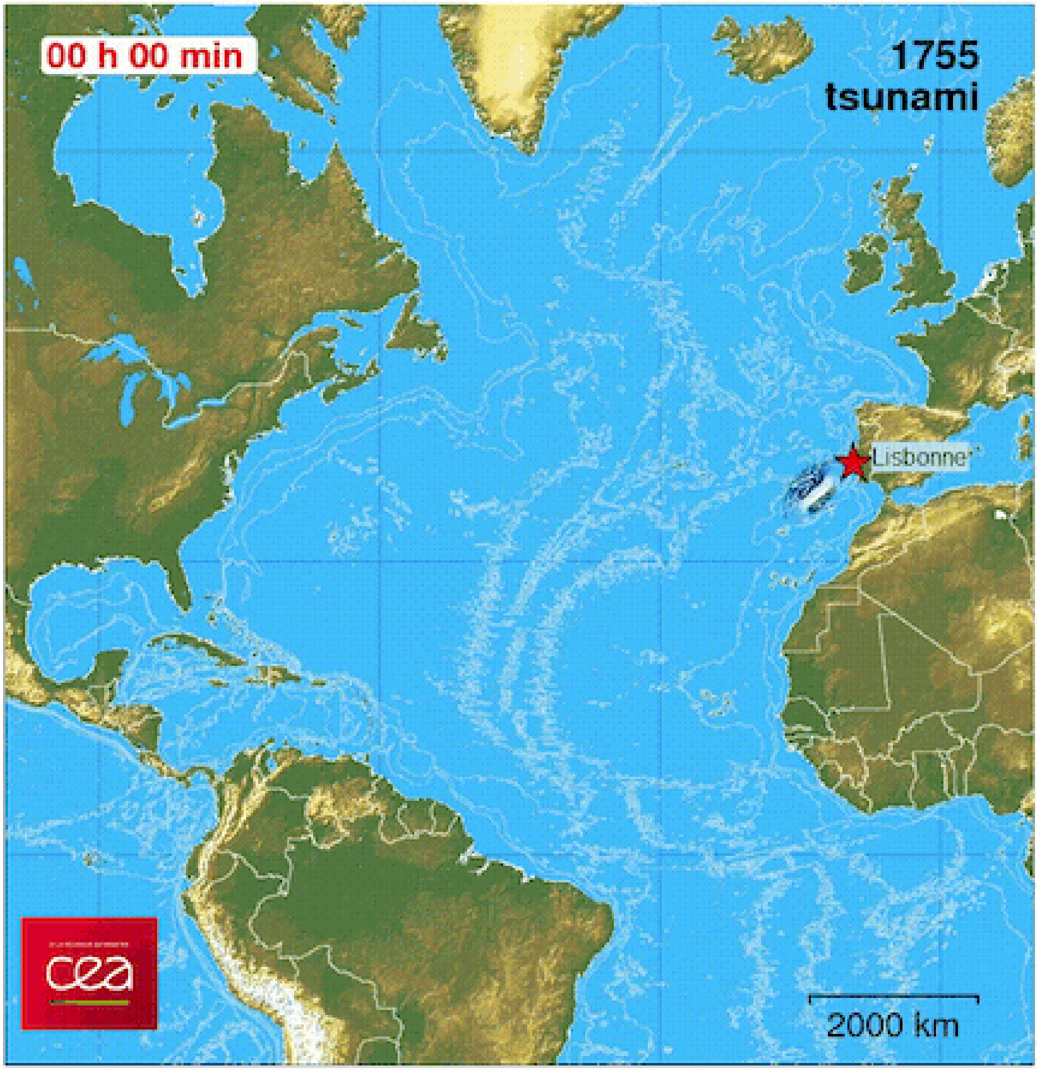


Well-known in the Pacific for many centuries, tsunamis [1] have been revealed worldwide following the catastrophic tsunamis of 2004 (Sumatra) and 2011 (Japan). Outside the Pacific, and throughout history, similar events are also well known. Thus in 1755, the Lisbon tsunami caused major damage in many European countries (mainly Portugal, Spain, but also Ireland, Great Britain...), African countries (Morocco), as well as in the West Indies. More recently, the tsunamis in 2018 in Palu or Krakatau (Indonesia) have emphasized these phenomena again, and recall the recurrent issues: has progress been made in understanding tsunamis, to better preventing them, or even considering their forecast? Whatever their origin (major earthquake or landslide), the coastal effects of tsunamis result in flooding several kilometres inland, run-up reaching several metres to tens of metres, strong currents in ports, often causing considerable destruction. Some tsunamis can be forecast/prevented by a warning system.

1. What is a tsunami?

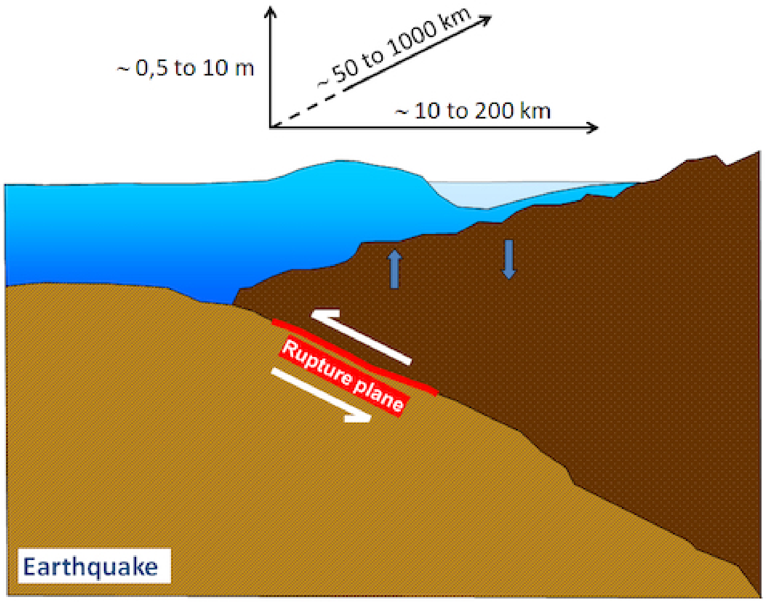


Figure 1. Tsunami triggered by a submarine earthquake, here on a cross-section of a subduction zone. At the time of rupture the crust near the trench uplift, while towards the coast it downlift, as shown by the blue arrows. [Source: Author]

2004 and 2011 tsunamis caused **considerable damage on** the coast, in areas that are highly vulnerable due to human, economic and tourism activities, and received a lot of media coverage. They also fostered a scientific revival aimed at better understanding and preventing these phenomena. The origin of tsunamis is linked to major **geological processes** such as earthquakes, volcanoes and landslides. Their damage is nowadays larger as coastal vulnerability is growing very rapidly.

Any motion that deforms the surface of the Earth's crust and is capable of impacting the surrounding water layers (ocean, sea, fjord, bay, lake, etc.), inducing **significant vertical deformation**, is likely to trigger a tsunami. The return to equilibrium of the water layer by the play of gravity forces induces the initiation and then the propagation of a **gravity wave** train. Through an amplification phenomenon when it reaches the coast, the tsunami can impact all the close and distant shorelines.

1.1. Triggered by an earthquake

Oceanic **subduction zones**, where one oceanic plate sinks under another tectonic plate, and which are associated with the most active volcanic chains (e.g. Indonesia, the West Indies, Japan, Chile, Peru, etc.), produce so-called **convergence** motion. They cause the largest known earthquakes (e.g. 365 in Greece, 1843 in the West Indies, 1957 in the Aleutians, 1960 in Chile, etc.), generally triggering tsunamis, five to ten times a century.

2004 and 2011 tsunamis were triggered by **subduction earthquakes** of **magnitude** [2] greater than 9. The rapid release, in a few minutes, of the elastic stresses accumulated over decades or even centuries of subduction (Figure 1) generates a vertical deformation of the water layer and initiates the tsunami.

The deformation of the overlying water layer has a vertical amplitude of the order of one to several metres. It extends over horizontal dimensions of a few tens to hundreds of kilometres in the direction of subduction, sometimes up to a thousand kilometres or more along the deep-sea trench. The latter **length** is generally **correlated with magnitude**, with orders of magnitude of 50 km (magnitude ~ 7.5), 200 km (magnitude ~ 8), 500 km (magnitude ~ 8.5) to 1000 km and more (magnitude ~ 9).

Submarine earthquakes **outside the subduction context** also produce tsunamis when the vertical deformation involved is significant:

for example, on 21 May 2003, an earthquake of magnitude 6.8 occurred off the coast of Algeria, in the Boumerdès region. This region of **active tectonic convergence** regularly produces major coastal and/or submarine earthquakes [3]; the fault planes [4] involved, which are fairly steep, favour sufficient vertical deformations from around magnitude 6.0;

similarly, the November 2004 earthquake in Les Saintes (West Indies), of magnitude 6.3, involved a **fault** in **extension**, or opening (the so-called normal fault) steep enough to produce vertical deformation that is more tsunamigenic;

lastly, earthquakes involving predominantly horizontal movements (the so-called **strike-slip** fault), with little vertical deformation, however, sometimes induce a tsunami. Tsunamis are amplified by horizontal movements of steep sea-bed topography close to the coast and/or by submarine rock avalanches triggered by seismic tremors (e.g. Izmit, Turkey, in August 1999, Haiti in January 2010, Palu in September 2018) [5].

1.2. Triggered by a gravity source

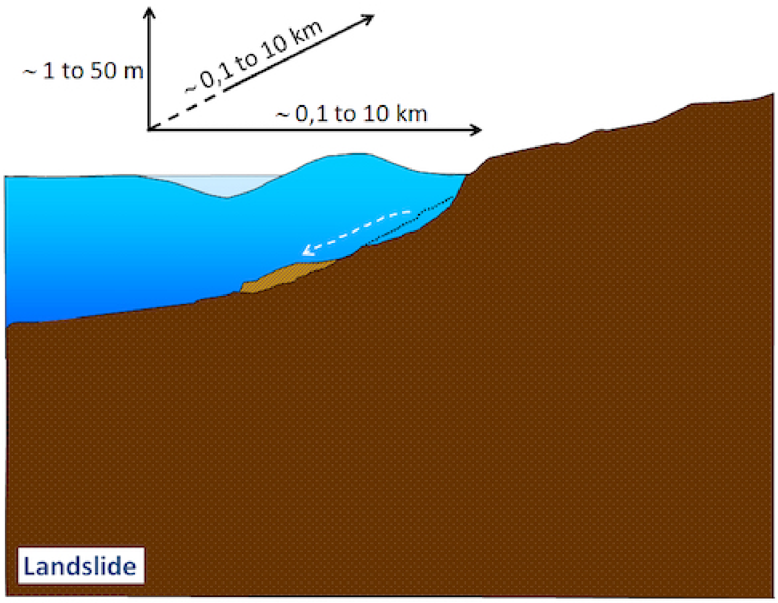


Figure 2. Tsunami triggered by landslide. The volume moving in the direction of the slope creates a depression on the water surface and a trough back up the slope. [Source: Author]

For a **landslide**, or rock avalanche (Figure 2), the volume is a few tens to hundreds of thousands of cubic metres, or even several cubic kilometres in the extreme. These collapses take from a few minutes to tens of minutes depending on the configuration and materials involved. The dimensions involved are less extensive horizontally, generally of the order of a few hundred metres to a few kilometres. On the other hand, the induced vertical deformation is generally of the order of one metre to several tens of metres.

Tsunamis generated by **volcanic collapses** have been very prominent in history, such as the eruption of Santorini in Greece (around 1600 BC), the explosion of the volcano Krakatoa (Indonesia) in 1883 (more than 30 m of tsunami in Probe Strait), and the explosion of Mount Pelee (Martinique, 1902) [6]

Rock avalanches, either completely or partially submarine, have also produced remarkable events, such as in the North Sea (Storegga, about 8000 years ago), in Lake Geneva in 563, at Nice airport in 1979. The numerous events also show the occurrence of such gravity-induced tsunamis following strong seismic tremors, as in 1958 in the Bay of Lituya (Alaska). Today, rock destabilisation occurs more frequently as a result of global warming, as in Greenland (in 2000, 2017) [7].

1.3. Physics of propagation

The excitation due to a sudden change in the sea floor causes the water body to rise and fall, resulting in the propagation of gravity waves in all directions.

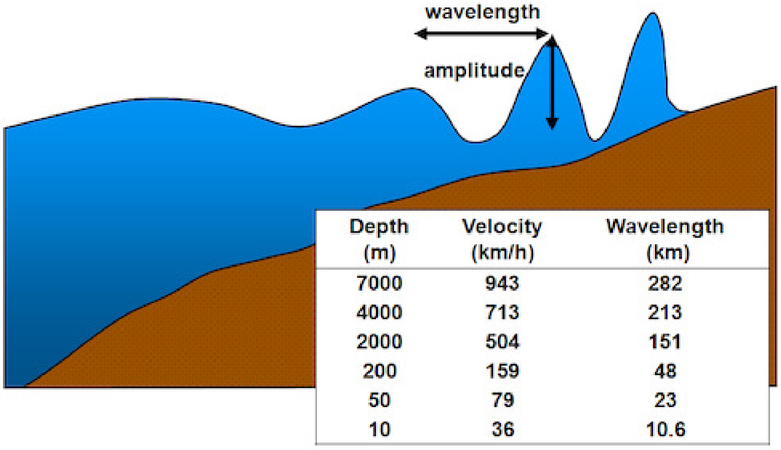
Several situations can be distinguished according to the type of source:

In the **case of earthquakes,** λ wavelengths are generally much greater than the water depth, which is a few hundred to a few thousand metres. This approximation, called "shallow water" or "thin layer", is used to express the first-order propagation velocity simply as $\sqrt{gh}$, where g is the gravity constant, and h is the water depth (see values in Figure 3).

The simplicity of this expression for velocity makes it possible to calculate, a few seconds after a submarine earthquake, the times of the first arrivals of the tsunami.

A seismic-type source produces imposes oscillations (or periods) of the water body approximately every **10 to 60 minutes**, depending on the extension of the source and the depth of water above. These periods remain dominant at first order during the propagation of the wave train.

For **landslides**, the wavelengths are shorter relative to the water depth, and the oscillations (periods) are close(about 1 to 10 min). In this case the speed of propagation also depends on the wavelength: shorter waves propagate more slowly than longer waves. The spreading of the different wavelengths leads to a more pronounced attenuation of the amplitudes: very high at the source, they decrease rapidly with distance.



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

Figure 3: Order of magnitude for tsunami propagation velocities and wavelengths. The diagram shows in particular how amplification is marked at the coast due to the decrease in velocity by a factor of 10 to 20. The period of the tsunami is initially defined by the characteristics of the source (dimensions, depth of overlying water). It remains similar to the first order during propagation. [Source: author]

In practice, the complexity of the tsunami source (3D geometry of the fault or collapse, dynamics of the rupture), gives a **spectrum** composed of multiple wavelengths, and **frequency dispersion** is observed almost systematically observed. Certain periods in this complex spectrum can be over-amplified at coastal sites, giving rise to **resonance** phenomena.

So the tsunami has a **geological origin**. However, there are also tsunamis of **atmospheric** origin. This is the case when a significant pressure gradient, of large spatial extent and associated with meteorological disturbances, moves on the water surface at a velocity of shallow waves (less than 200 m). A resonance (known as Proudman resonance) can then generate the propagation of a tsunami-like wave train, known as a **meteotsunami**, whose periods of 5 to 15 minutes are similar to those of a tsunami. These phenomena are frequently observed in regions where the seabed is shallow (Adriatic Sea, the Balearic Rissagas, Sea of Japan, etc.). Their effects can be destructive.

Generally speaking, a tsunami is therefore made up of a series of waves, which amplitude depends on the water depth. Near the source its amplitude can be a few meters, but the attenuation during propagation leads to amplitudes offshore to a few centimeters to tens of centimeters. Then as it approaches the coast (Figure 3) the influence of the way the water depth decreases, becomes considerable. A steep slope tends to reflect waves. On the other hand, a gently sloping bottom slows down the waves by a factor of 5 to 20, and thus tightens the wave train. This results in a corresponding increase in the amplitude of the waves: the **tsunami is amplified at the coast**, where it then potentially invades the shoreline.

1.4. Effects on the coast

The impact of the tsunami on the coast results in a **succession of ebbs and flows of** the sea, of varying amplitude over time. These sea motions can lead successively to inundation of the shoreline and recessions, beyond the usual low tide levels in the case of major tsunamis. **Bore** phenomena in rivers or canals are frequently observed as a result of rising water levels. On the other hand, although not systematic, the arrival of a tsunami can start with a recession of water initially at rest, which is a major warning signal, all the more striking in low-tide areas, and especially if a tremor has been felt.

The periods, depending on the event, range a few minutes to sometimes about 60 minutes, and the phenomenon at the coast lasts for **several hours**. Usually the highest waves are observed during the first two hours, but late arrivals several hours later may produce significant effects, and the return to normal state usually occurs at least 24 hours after the first arrival.

Figure 4. (a) Arrival of the 2011 tsunami in Miyako Bay, and overflow of the protective wall (source: Flickr) (b) Three-storey building overturned by the tsunami in Onagawa (source: International Tsunami Information Center) (c) Impact of the 2011 tsunami in Taipivai Bay at Nuku-Hiva in the Marquesas Islands (French Polynesia), the tsunami widened the riverbed by digging the banks to a height of about 3 m. [Source: © CEA]

These coastal observations of tsunamis have particular **names** in several languages: the Japanese tsunami (literally: wave in the harbor) is thus the same phenomenon as the *maremoto* in Italian or Spanish, sea motion, or the *tai toko* (big wave) in the Marquesas Islands. In French, the term **raz-de-marée** is often put forward as describing a tsunami, but it refers to an exceptional inundation of meteorological origin, also known as “surcote”, and does not present a precursor recession (physically, a tsunami could be seen as a succession of several tidal waves, generally supplemented by significant recessions).

Coastal phenomena result in **complex hydraulic effects**. Even not inundating, in relatively moderate cases, tsunamis with less than 1 m amplitude create rise and **strong currents** in ports or bays, sometimes with eddies at the end of the dikes, all of which can potentially disrupt navigation and port infrastructure. For tsunamis producing inundation inland, it can be noted that waves as low as **50 cm flowdepth** can destroy facilities, and are capable of displacing light vehicles and hitting standing people. A lot of debris is potentially carried along, and the destructive power increases as it is carried along. Extreme tsunamis destroy virtually **any construction**, sometimes up to several kilometres inland.

Figure 4 shows how the water body in Miyako Bay (Iwate Prefecture, Japan) is flooded when the 2011 tsunami arrives, 30 to 40 minutes after the earthquake: the tsunami is not an isolated wave, but a **rise in the water level for several minutes**, capable of overflowing and destroying protective sea walls and gates. The power of the sea’s **floods** (ebb and flow) causes a great deal of destruction, and is capable of overturning constructions without solid foundations (Figure 4, right).

2. How to observe and study a tsunami

2.1. Sea level measurements from open sea to coast

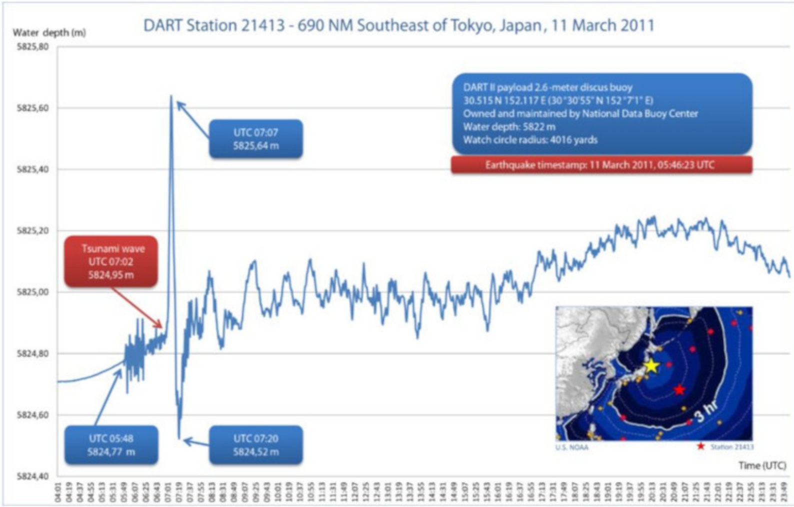


Figure 5. Measurement of a tsunami via a DART buoy, located at 1h30 propagation time from the epicentre of the 2011 earthquake (location of the buoy on the red star in the insert). The first wave of this exceptional tsunami reached an amplitude of 1 m at this location, and the record shows the time series of the following waves, with an average amplitude of 5 to 10 cm, here for about 15 h [Source: Wikipedia, GNU Free License]

Offshore, the amplitudes and wavelengths of tsunamis make them **imperceptible** to boats. Just since the end of the 20th century instruments are able to measure them, via the variation in hydrostatic pressure due to the wave path. Since the 1990s, **pressure sensors** have been deployed on the ocean floor, transmitting the data acoustically to a surface buoy, which transmits the data remotely by satellite (see also Focus 1) (Figure 5).

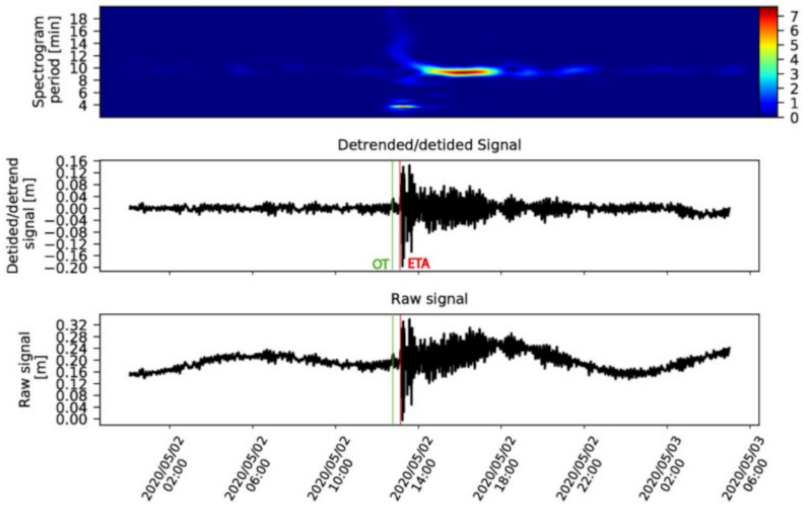


Figure 6. Example of the recording of a tsunami on 02 May 2020 in Crete (Lerapetra site), following an earthquake of magnitude 6.6. From top to bottom: values of dominant periods during 24 h, showing a dominant period of 10 min (in red) which may correspond to a local resonance for about 6 hours, filtered tide gauge, raw tide gauge. Green line: origin time of the earthquake (EO). Red line: theoretical time of the 1st arrival of the tsunami - estimated time of arrival (ETA) [Source: © CEA]

At the coast, **tide gauges** measure the temporal variation of the sea level recorded in the ports (Focus 1), including the tsunamis waves. This type of record shows the successive wave packets of tsunamis, as well as the agitation of the bay maintained over a period of 20 hours or more. The **resonance effects** specific to the bay [8], are similar to those occurring during site effects due to earthquakes, for example in sedimentary valleys. Some bays are more amplifying than others, depending on their geometry and average depth. Good quality data are available to measure the dominant amplitudes and periods of the signal over time (Figure 6).

Port tide gauges have been significantly upgraded since the 2004 tsunami, which led to the deployment of warning systems requiring this type of properly sampled measurements to monitor the tsunamis propagation. Having **properly specified instruments** for tsunami measurements is still needed in some basins, especially for all short-period events (landslides).

2.2. Complementary measures

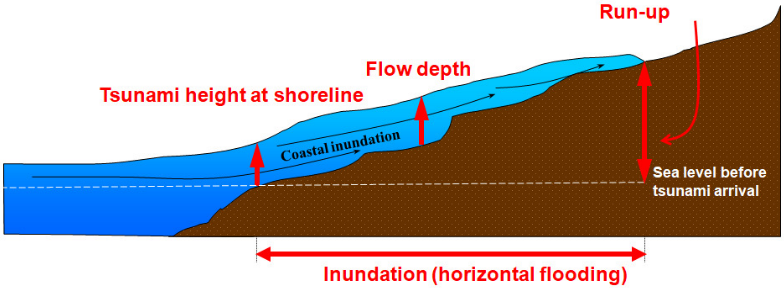


Figure 7. Field measurements of the impact of a tsunami on the coast. [Source: Author]

All harbours and bays are not equipped with tide gauges and tsunamis must also be characterized after their path. **Field surveys** will quickly measure the traces, and evaluate the tsunami heights during the inundation, as well as the maximum altitude reached (called run-up), the maximum horizontal length of the inundation (Figure 7). These measurements give not real indication of the tsunami waveform. However, nowadays digital analyses of witness videos often complement these data, which allow to build equivalent tide gauges record, or give information to the extent of the initial retreat of the sea.

Other physical measurements provide information: GPS sensors deployed on buoys, satellite data, analysis of the total electronic content of the **ionosphere** [9] (see Focus 1).

3. Preparing for a tsunami

3.1. Catalogues and statistics

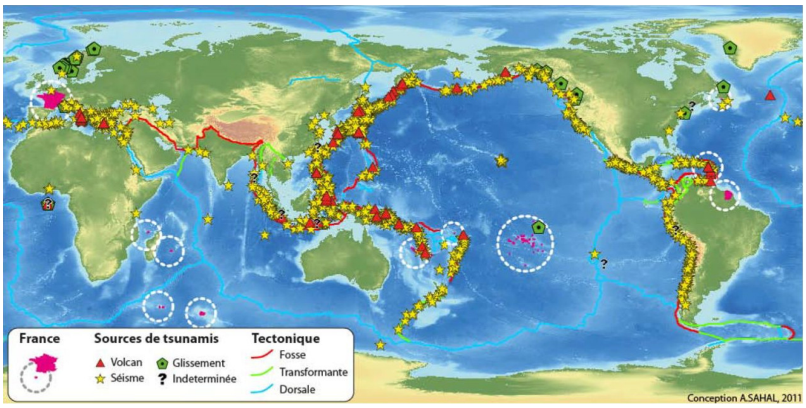


Figure 8. Sources of known tsunamis from -2000 to 2011 according to the US National Ocean and Atmosphere Administration (NOAA) global database [Source: [10]]

Historical catalogues are very heterogeneous depending on the region, and generally before the middle of the 20th century, only extreme tsunamis are listed. It is possible to correlate them with the **seismicity catalogues**, which confirms that the sources of known tsunamis are mostly located on large seismic active areas, especially on **subduction zones** (Figure 8). All French territories are concerned, either directly on subduction zones (West Indies), or more remotely, exposed to tsunami amplification after propagation.

The **Pacific Ocean** is the region where the majority of tsunamis occur, and earthquakes are their main origin. Time analysis is biased due to the **short period of time available** for a complete analysis. Thus, very rare events known to have occurred in the past are not represented (e.g., the great tsunami of 365 in western Crete), as well as cases of tsunamis in periods not easily documented historically (e.g., the West Indies before the 15th century).

These statistics should be considered as first element in assessing the **hazard** for a specific region; earthquakes are not predictable but always occur in **active areas**, with **various return periods**, associated tsunamis would occur repeatedly.

3.2. Hazard studies and tsunami modelling

Since the 1980s, **numerical simulation** has provided an increasing number of quantitative elements to assess the tsunami hazard. Earlier models, based on ray tracing in a variable-velocity medium (the ocean), already took advantage of the increasingly well known **global bathymetry** to calculate travel times as a function of water depth (Figure 9).

Starting in the 1990s, simulation methods, generally in the form of **numerical methods**, made it possible to integrate the source model (seismic, gravity collapse) [11], coupled with a wave propagation model, and finally with a coastal impact model. The complex steps to be modelled are the source and the coastal impact, two areas where the physical complexities require either very advanced models, sometimes in three dimensions, or approximations whose limits must be known.

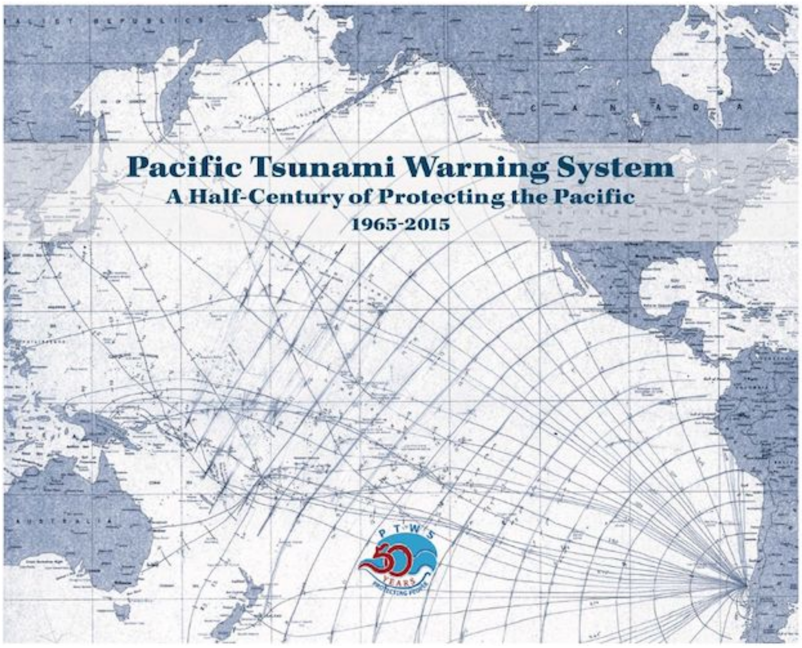


Figure 9. Cover of a book celebrating the 50th anniversary of the Pacific Warning System in 2015, and recalling the first grape tracings made for the 1960 earthquake in southern Chile, allowing isochrons to be traced from the epicentre [Source: IOC UNESCO] - Vidéo Tsunami Chili 1960

At the source, the initial deformations due to an earthquake can be modelled using **elastic models** whose parameterisation depends on seismological studies. In the case of a gravity collapse, the parameterization is more complex and depends on the materials, geometry and dynamics of the landslide. In all cases, **in situ data are scarce** and models are based on the interpretation and inversion of seismic or geodetic data.

During **propagation**, the long-wave approximation described above allows the evolution of the wave train to be simulated using the equations of fluid mechanics in two horizontal dimensions.

At the coast, the non-linear amplification must be resolved, and the narrowing of wavelengths requires knowing the velocity, and therefore the bathymetry, very finely. Typically, to model a tsunami at the harbour scale, the "gridsize" of the models must be **less than 20 m**. Finally, land-based modelling requires a good knowledge of the **topography** at the same resolution, and the equations to be solved can take into account the interaction of the waves with the buildings and vegetation.

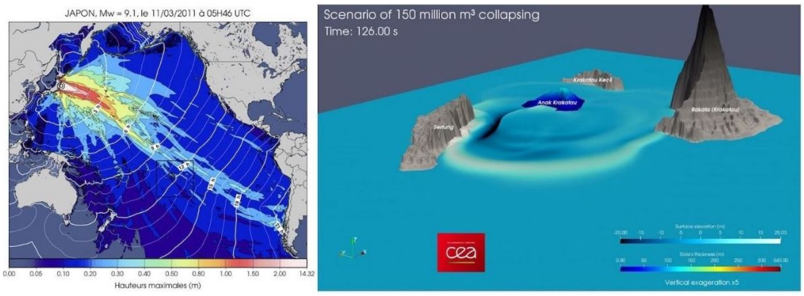


Figure 10. (Top) Simulation of the 2011 tsunami across the Pacific, showing propagation times and focusing of maximum heights in a preferential direction, close to Polynesia (source CEA). (Bottom) Numerical simulation of the tsunami following the collapse of Krakatau in December 2018, about 2 min after the triggering (north in the y direction) [Source: A. Paris, CEA] - Video 2011 HMAX

If data are available, a tsunami can then be **reproduced digitally**, from its origin, its propagation, to the impact at the coast (Figure 10). These approaches allow a better understanding of the physical processes, explain the observations, and also predict effects for some possible **scenarios**, thus contributing to the development of prevention studies (see for example [12]).

3.3. Coastal exposure and shoreline preparation

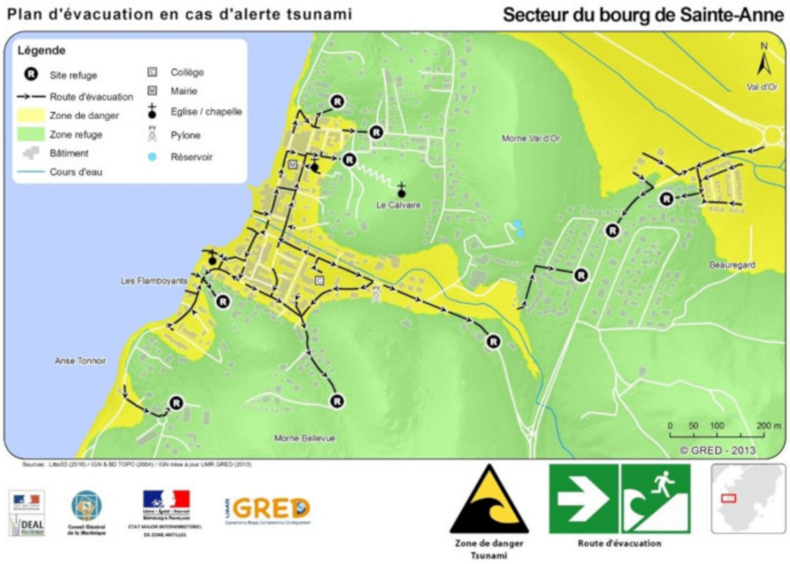


Figure 11. Example of an evacuation plan in Martinique, based on an impact 10 m altitude [Source: [13]]

Using historical catalogues and simulation results, **risk prevention plans** can be drawn up. Exposed area maps are important tools to assist in coastal **planning**, public **awareness**, evacuation planning (e.g. Figure 11 and Figure 12) and emergency response planning, all of which can be used to prepare the coastline exposed to the tsunami hazard.

4. Forecasting tsunami impacts

4.1. Tsunami warning systems

Figure 12. Signages in French Polynesia, from left to right, for exposed areas, a refuge site, and the evacuation route [Source: © CEA]

Tsunami warning systems are based on **operational centres** capable of 1/ using seismic data to detect and characterize earthquakes and sea level measurement data to detect and measure waves, then 2/ transmitting warning messages to civil protection authorities and foreign recipients.

The first **national warning centres** were established in the mid-20th century by the United States, followed by Japan, Russia, Chile and France (in French Polynesia, see Focus 2), following major tsunami disasters (Aleutians 1946, Kamchatka 1952, and Chile 1960). In 1965, following the establishment at Unesco of the **Intergovernmental Oceanographic Commission** (IOC), the **International Co-ordination Group** (ICG) of the Tsunami Warning System in the Pacific was established to warn Pacific states in the event of a major earthquake that could cause a tsunami.

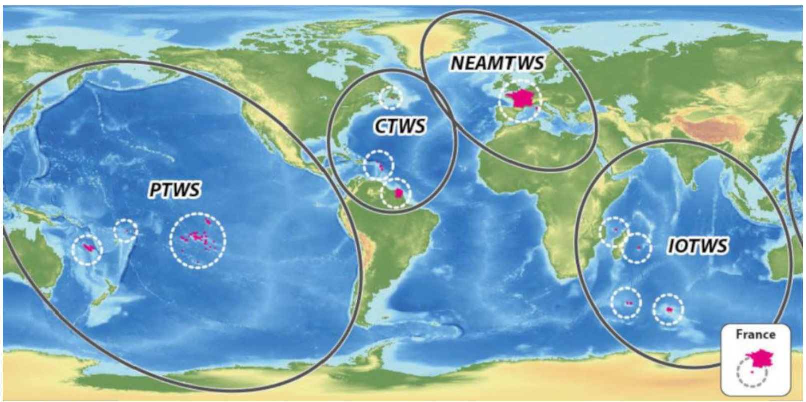


Figure 13. Areas of responsibility of the four regional intergovernmental coordination groups for, from west to east, the Pacific, the Caribbean, the North-East Atlantic and Mediterranean, and the Indian Ocean [Source: SAHAL, A. (2011)]

The last major breakthrough was the response to the major Indian Ocean tsunami of December 2004. The IOC then established **three new ICGs** to cover the Indian Ocean, the Caribbean, the North-East Atlantic, the Mediterranean and Connected Seas, and a global working group.

These groups are responsible for defining the architecture and coordinating the establishment of the warning systems and encourage all Member States to contribute to and participate in the activities. The **three pillars of the warning systems** are: (i) hazard and risk assessment; (ii) monitoring and warning; and (iii) prevention and mitigation.

Since 2012, the four ocean basins (Figure 13) are monitored and alerted by 11 tsunami service providers.

4.2. Operational forecasting of tsunami impacts

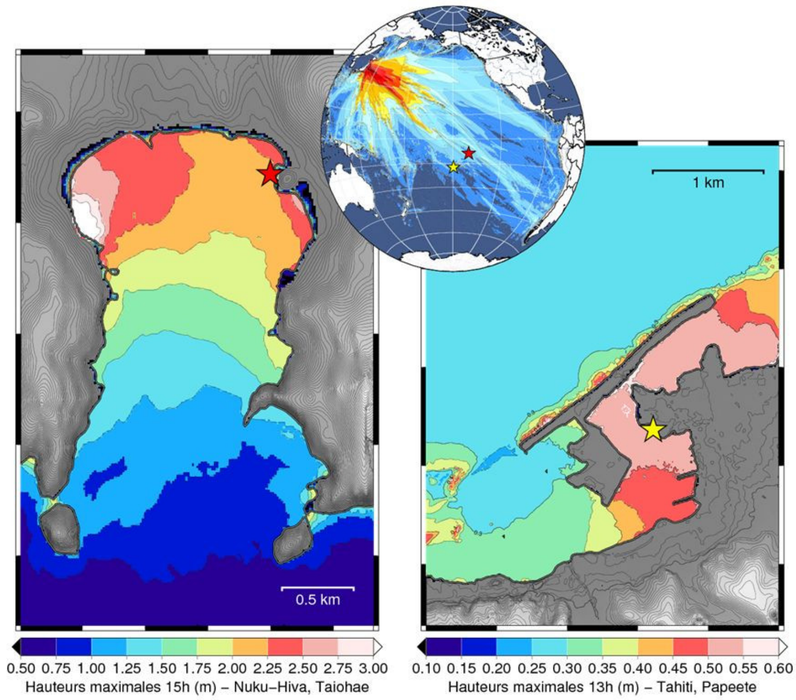


Figure 14. Example of two maps of maximum heights estimated by the multi-grid simulation under alert conditions. (a): for Taiohae Bay (the red star indicates the location of the Nuku-Hiva tide gauge). (b): for the port of Tahiti on the right (the orange star indicates the location of the Papeete tide gauge). [Source: Author]

In tsunami warning centres (see Focus 2 for France and French Polynesia), the parameters of the seismic source (location, depth of the hypocentre, magnitude, rupture duration, focal mechanism and fault dimensions) are automatically evaluated using data from real-time **seismic stations**.

The source parameters are used to calculate the coseismic deformations and then to simulate the tsunami propagation. Arrival times are calculated and tsunami heights are then estimated in the form of **forecast inundation maps**. In French Polynesia, where propagation times are generally more than 7 to 8 hours (except for sources in the Southwest Pacific), these simulation results allow the expected tsunami heights to be specified down to the coastal detail level (Figure 14). This information is **transmitted to the Civil Protection** to decide whether or not to create a crisis cell for the management of the tsunami warning in progress.

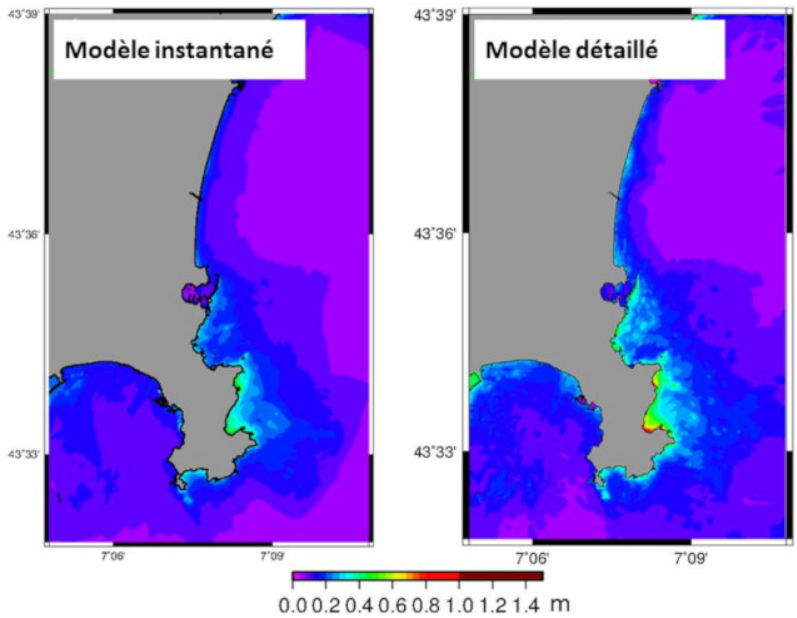


Figure 15. Simulation of maximum tsunami heights in Antibes following a magnitude 7.1 earthquake in eastern Algeria. The model is calculated in detail with a long method (right), and is used for a rapid method in the context of an alert (left). [Source: author]

At **Cenalt** [14], numerical simulations of tsunami remain too time consuming to be carried out at the scale of ports and bays, in the 15 min interval following the earthquake. Estimates are therefore still flat-rate (decision matrix). Current developments concern rapid methods, for example to approximate the response of a bay from parameters obtained with a family of detailed models (Figure 15) [15]. The common goal is still to establish **estimates at the coast**, sufficiently in advance of the arrival of the tsunami, to organise evacuations and sheltering.

5. Messages to remember

Tsunamis have a **geological cause**, and are able to hit close and remote **coastlines** where they can inundate and cause major **destruction**.

The **Pacific Ocean** is the most exposed region due to its tectonic activity;

However, all ocean and sea basins can be affected, especially in **tectonic** and **volcanic** areas, more or less frequently;

Data needed to monitor a tsunami are **seismic data** and **sea level** measurements from open sea to coast;

Outside the Pacific, which has already been equipped since the 1960s, **warning systems** have been built in other basins between 2005 and 2012;

Numerical simulation allows a tsunami to be simulated from its initiation to coastal inundation, and is all the more efficient if the numerical tools are regularly compared with seismic and sea level data;

Warning systems are effective if the **data** are **numerous**, transmitted and analysed in **real time**, and comparable to high-performance numerical models;

Warning messages are effective when **risk awareness** is developed, based on education of the general public and training of the authorities: repeated exercises are necessary to prepare;

A better education and understanding of the phenomena is essential for the **prevention of** exposed **populations**, and it must be coupled with political decisions for an adapted development of the coastline (signalling, constructability, evacuation...).

It is under these conditions that tsunamis, sometimes very rare, sometimes surprising, and still forgotten or underestimated in many regions, can be **properly prevented** and mitigated the next time they occur.

This article is based on contributions from the two lead authors, as well as A. Gailler, P. Heinrich and A. Paris (CEA, DAM, DIF, Arpajon) as well as A. Jamelot, O. Hyvernaud and D. Reymond (Laboratoire de Géophysique de Pamatai, French Polynesia).

Notes and References

Cover image. Modelling of the surface of the Atlantic Ocean, for a scenario similar to the tsunami resulting from the Lisbon earthquake of 1755, extracted after 3 hours of propagation

[1] Propagation of waves in an ocean or a sea, following an underwater geological phenomenon (earthquake, landslide or volcanic explosion). The tsunami is greatly amplified when it arrives at the coasts where it can cause major flooding.

[2] Dimensionless quantity characterizing the energy released by the seismic source. A unit of magnitude corresponds to an energy multiplied by 30.

[3] ROGER, J. (2011) *Tsunamis générés par des séismes au niveau de la zone de collision entre les plaques africaine et eurasienne : études de cas pour l'évaluation du risque tsunami en Méditerranée occidentale et Atlantique nord*. Doctoral thesis, Université Pierre et Marie Curie, 347 p.

[4] A fault is a fracture plane that divides a boulder into two compartments or separates two tectonic plates

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