Optimal positioning of two deep ocean bottom pressure gauges for tsunami wave detection in the western Ionian Sea

NH5.1 | EGU24-18892 | X4.68

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Abstract

Tsunami warning and forecasting largely benefit from using offshore bottom pressure gauges (OBPG); these sensors, installed far offshore and typically close to causative sources, can measure the tsunami waves before reaching the coasts to maximize the lead time for alerting. Most of these sensors are installed around the Pacific Ring of Fire (e.g., DART buoys, S-NET), which hosts ~90% of the global seismicity and most significant tsunamigenic earthquakes. Even though less frequent than in the Pacific Ocean, tsunamigenic earthquakes can also occur in the Mediterranean Sea (e.g., the M8+ 365 AD in Crete or the M7 2020 Samos earthquakes), in which the Ionian Sea is characterized by relatively high tsunami hazard (Basili et al., 2021). However, offshore sensors are not present in the Mediterranean Sea and the Tsunami Service Providers operating in the basin (CAT-INGV for Italy, NOA for Greece, KOERI for Türkiye, and CENALT for France) can rely for the tsunami monitoring activities only on the coastal tide gauges networks. One of the objectives of the Italian MEET project (MONITORING EARTH'S EVOLUTION AND TECTONICS), in the framework of the National Recovery and Resilience Plan (PNRR) funded by EU, is the deployment of two OBPGs offshore the Italian coasts. To maximize the lead time gain and due to the high cost of the instruments (including both the maintenance and installation), a careful analysis of the optimal locations where to deploy these instruments is required. Here, we present the results of the study carried out to identify the more suitable locations to deploy two OBPGs offshore the Ionian coasts of southern Italy. The method proposed considers an ensemble composed of more than 150k scenarios selected from the NEAMTHM18 regional tsunami hazard model; these scenarios are the ones capable of causing at least a 20 cm tsunami height in front of the Ionian coasts of Italy. For each scenario, we compute i) the tsunami detection times for each point within a target area (i.e., more than 200 possible locations) where the OBPG deployment is envisaged, and ii) the tsunami detection times at all tide-gauges on the coasts of the Ionian Sea. The optimal location for the two OBPGs is established by minimizing a cost function which is a summation of the minimum travel times, for each potential tsunami source, to all available existing coastal gauges and all the potential pairs of OBPGs, weighted by the rate of occurrence of each individual source according to NEAMTHM18.

Why in the Mediterranean?

Mediterranean Sea historically hosted tsunamigenic events (seismically induced and not); Tsunami Service Providers in the Mediterranean can monitor the tsunami evolution only by means of tide-gauges.

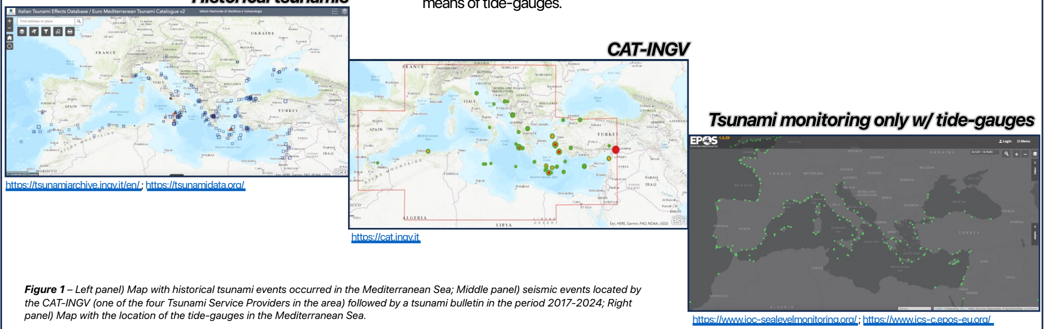

Figure 1 – Left panel) Map with historical tsunami events occurred in the Mediterranean Sea; Middle panel) seismic events located by the CAT-INGV (one of the four Tsunami Service Providers in the area) followed by a tsunami bulletin in the period 2017-2024; Right panel) Map with the location of the tide-gauges in the Mediterranean Sea.

How many and where?

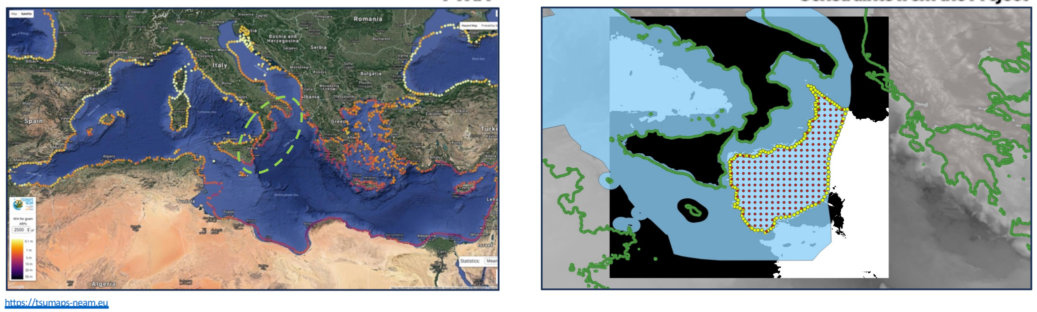

Figure 2 – Left panel) NEAMTHM18 tsunami hazard map (mean and average return period of 2500 years); Right panel) Map showing the Exclusive Economic Zone (EEZ, cyan), the candidate points to deploy the OBPGs (red dots), the offshore POIs (green dots), and the bathymetric depth boundary for the analysis (yellow dots).

The selection of the area where deploying the 2 OBPGs is PTHA-driven; specifically, we individuate the Ionian sea, where the Italian coasts are characterised by the highest tsunami hazard level based on the long-term NEAMTHM18 model (green ellipse in the left panel of Fig. 2). Furthermore, based on the MEET Project rules, the OBPGs must be deployed inside the Italian Exclusive Economic Zone (EEZ, right panel in Fig. 2). Given these constraints and that the sea depth in the selected area ranges between [2000-4000 m], we selected 229 candidate points with a mutual distance of ~18 km where the OBPGs can be deployed (right panel in Fig. 2)

PTHA disaggregation

The optimal positions result from the analysis of the tsunami detection time for an ensemble of earthquake scenarios. The ensemble is built by performing a disaggregation from long-term PTHA model (NEAMTHM18) on the POIs (Points of Interest) close to the Ionian Italian coasts (see green ellipse in Fig. 2). The disaggregation algorithm selects all the scenarios (ranked by the annual rate) contributing to the POIs for given intensities, or intensity intervals, such that reproducing for each POI the entire original hazard curve with a given level of accuracy. Here, we selected [0.3-0.5-1-4-8 m] as wave amplitude thresholds (i.e. intensity thresholds) and 95% as level of accuracy. The ensemble is composed by ~190k scenarios (Fig. 3).

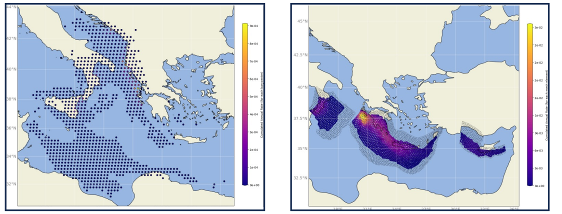

Figure 3 – The distribution of seismic sources (Background seismicity to the left, Subduction sources to the right) identified through disaggregation of the NEAMTHM18 hazard curves for the POIs in the green ellipse of Fig. 2 - the colour scale is the cumulative annual rates for each position.

For each earthquake of the ensemble a tsunami scenario is simulated:
Code: Tsunami-HySEA
Bathymetry: 30 arc-sec
Simulation time: 8 hrs
Time-series: candidate points + POIs (2km spaced, 50m depth); output sampling at 30 s

Optimal positioning

GOAL: minimising the detection time (the cost function) for scenarios resulting in at least 1 coastal point with H >= 0.2m (after applying the Green's law, GL) along the Ionian coasts of Italy and considering the scenarios likelihood (i.e., the annual rates); the optimal OBPG positions will consider also the current tide-gauges network in the Mediterranean Sea.

ALGORITHM:

- Scenarios Filter 1: retain only the scenarios with maximum wave amplitude >= 0.2 m (after GL) for at least one POI
- Scenarios Filter 2: retain only the scenarios with maximum wave amplitude >= 0.03 m for at least one candidate position
- Retrieve the mean annual rates for the remaining scenarios after the filters
- Compute the time to overcome the threshold of 0.03 m for each possible pair of OBPG positions (i,j) and the time to overcome the threshold of 0.20 m for all the tide gauges in the MED {m_k, k=1,K}
- The detection time for each tide-gauge is delayed by a quantity depending on the distance between the 50 m isobath and the actual tide-gauge position
- Retain only the pairs of OBPGs with a mutual distance > 100 km
- For each possible pair of OBPG positions and for each scenario, take the minimum detection time between the tide-gauges {m_k}, $OBPG_i$ and $OBPG_j$
- Weight the detection time by the scenario's rate
- Sum up over all the scenarios and normalise to obtain the cost function C
- The minimum of C corresponds to the optimal pair of OBPG positions

$$C_{ij} = \frac{1}{\sum_{S=1}^{N} \lambda_S * \delta_{TG}^S} * \sum_{S=1}^{N} \lambda_S * \delta_{TG}^S$$

$\delta_{TG}^S = 0$ if $min\{TG\} < tOBPG1$ and $min\{TG\} < tOBPG2$

$\delta_{TG}^S = 1$ if $tOBPG1 \leq min\{TG\}$ or $tOBPG2 \leq min\{TG\}$

With:
N the total number of scenarios (S)
tOBPG1 and ***tOBPG2*** the candidate pair of OBPGs
λ_s the annual scenario's rate

Results

The optimal OBPG positions corresponding to the minimum of the cost function are located offshore Ionian Calabria, far ~100 km from the coast and at the depth of ~2200-2600 m (cyan triangles in Fig. 4).

To take into account the uncertainty in the OBPG estimation, we consider the OBPG pairs corresponding to the 200 cost functions closest to the global minimum; the pattern of these positions highlights 2 spatial clusters; then we can consider as the optimal positions the barycentres of these clusters. They are located offshore Ionian Calabria and south-eastern Sicily, far ~100 km from the coast and at the depth of ~2600-3200 m (white triangles in Fig. 4).

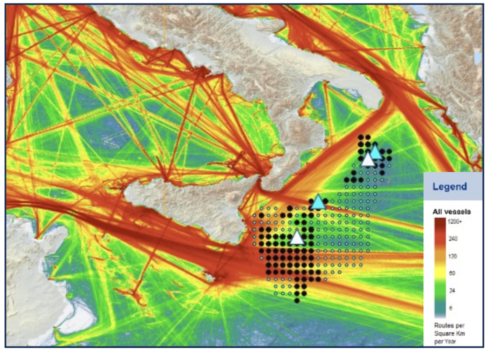

Figure 4 – Optimal OBPG positions corresponding to the minimum of the cost function (cyan triangles), and to the barycenters of two cluster of positions (black dots) representing the variability of the optimal solution around the minimum of the cost function (white triangles). In background is shown the density maritime routes map (2022).

We evaluate the tsunami detection time considering the scenario ensemble from the PTHA disaggregation (weighted by the earthquake annual rates), by using

- **the existing tide-gauges network only**
- **the existing tide-gauges network + 2 OBPGs (minimum cost function)**
- **the existing tide-gauges network + 2 OBPGs (barycenter positions)**

The average detection time is <~4 min when OBPGs are present; using the barycenter positions the results are similar; then the barycenter positions are preferred because do not interfer with high density maritime routes.

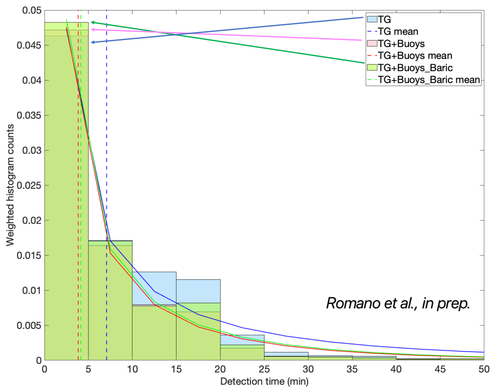

Figure 5 – Tsunami detection time distribution for the existing tide-gauges network only (blue), the existing tide-gauges network + 2 OBPGs (minimum cost function, pink), the existing tide-gauges network + 2 OBPGs (barycenter positions, green).