# Numerical simulation of tsunami propagation near the French coast of the Mediterranean

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**Abstract.** The problem of tsunami risk for the French coast of the Mediterranean is discussed. Historical data of tsunami manifestation on the French coast is described and analyzed. Numerical simulation of potential tsunamis in the Ligurian Sea is done and the tsunami wave height distribution along the French coast is calculated. The effect of far tsunamis generated in southern Italy and the Algerian coast is also studied.

## 1. Introduction

The study of tsunami risk for the French coasts of the Mediterranean is a difficult problem. Indeed, tsunamis are rather rare events in France and the lack of data for past tsunamis makes a direct estimation of tsunami risk difficult. For preliminary estimates of this risk, the synthetic method may be applied (Curtis and Pelinovsky, 1999). It is based on the wide application of numerical simulations of real events and of possible tsunamis from different hypothetical sources whose characteristics are chosen from historical data and analysis of the seismicity for a given area. This approach allows comparing the possible characteristics of tsunamis in different coastal points and gives preliminary estimates of the tsunami risk. This method was used in order to analyze the tsunami propagation and manifestation in the vicinity of the Mediterranean French coasts.

## 2. Analysis of Historical Data

Data of historical tsunamis from 2000 BC to 1991 AD in the Mediterranean are collected in the catalogue of Soloviev *et al.* (1997). According to this catalogue, the total number of events for the Ligurian Sea (part of the Mediterranean including the French and northeastern Italian coasts) is 36. The return period is estimated at 17 years, the mean intensity of tsunami is 3.8, and the maximum intensity is 4. The probability of a possible new tsunami

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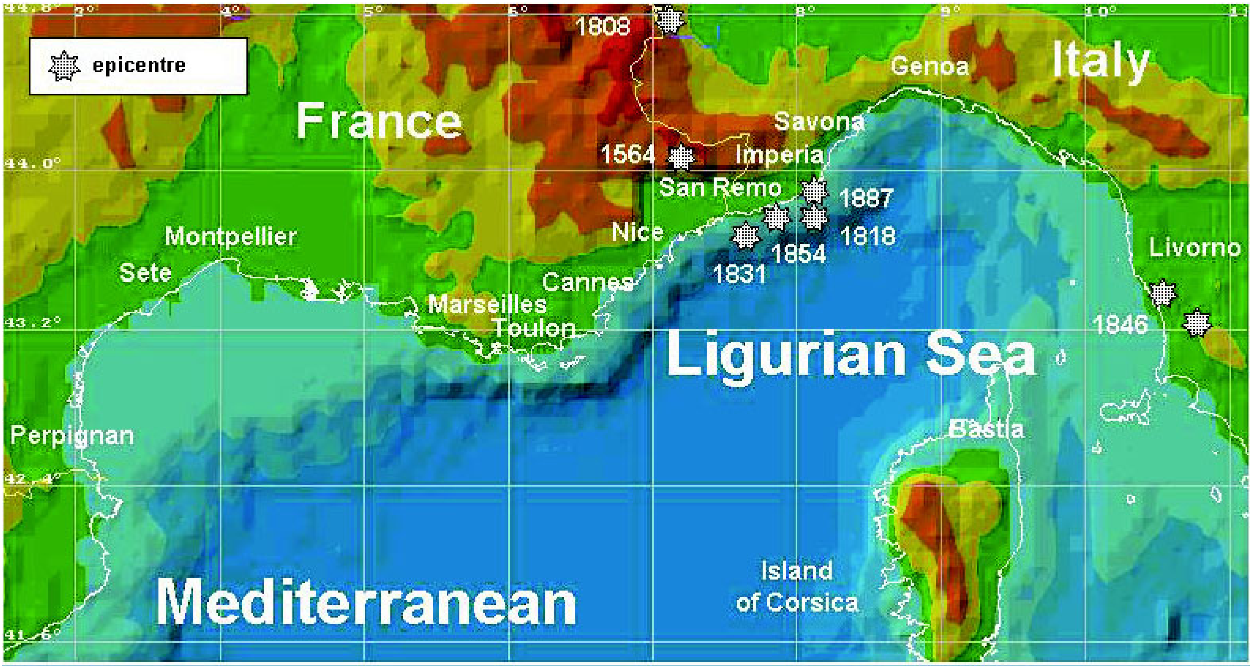


**Figure 1**: Epicenters of earthquake-induced tsunamis on the French coast of Mediterranean.

in the Ligurian Sea is considered high. Also, Tinti and Maramai (1996) prepared a catalogue of tsunamis generated in Italy and in Cote d'Azur, France. According to both catalogues, there were 24 events of tsunamis on the French coast of the Mediterranean, and most of them (20) occurred in the 19th century. The return period of tsunamis for the Mediterranean French coasts can be estimated at 18 years. At Nice–Cannes 13 events were observed, 5 at Marseilles, 3 at Sète, and 2 at Corsica. Earthquakes are responsible for 11 tsunamis, submarine landslides for one tsunami, and unknown sources for 12 tsunamis. There is poor information on tsunamigenic earthquakes and the earthquake magnitude is known for only four events (1564, 1808, 1846, and 1887). Furthermore, there are no data of tsunami run-up heights for almost all events. Only the tsunami of 23 February 1887 is well documented. The epicenters of past tsunamigenic earthquakes for the French coasts are presented in Fig. 1. In fact, all tsunamigenic earthquakes can be divided into three groups. The first group corresponds to earthquakes in the vicinity of the French coast (Nice–Imperia). The second group represents the two "land" earthquakes (1564, 1808), and the third one, far earthquakes on the western coasts of Italy.

## 3. Mathematical Model

Usually, tsunami waves are low-frequency long waves, and the appropriate mathematical model is the shallow-water theory, for instance, in the form of

Saint-Venant equations

$$\frac{\partial \eta}{\partial t} = \frac{\partial M}{\partial x} + \frac{\partial N}{\partial y}, \tag{1}$$

$$\frac{\partial M}{\partial t} + \frac{\partial}{\partial x}\left(\frac{M^2}{D}\right) + \frac{\partial}{\partial y}\left(\frac{MN}{D}\right) + gD\frac{\partial \eta}{\partial x} + \frac{gm^2}{D^{7/3}} M\sqrt{M^2+N^2} = 0, \tag{2}$$

$$\frac{\partial N}{\partial t} + \frac{\partial}{\partial x}\left(\frac{MN}{D}\right) + \frac{\partial}{\partial y}\left(\frac{N^2}{D}\right) + gD\frac{\partial \eta}{\partial y} + \frac{gm^2}{D^{7/3}} N\sqrt{M^2+N^2} = 0, \tag{3}$$

where $M$ and $N$ are the horizontal components of the discharge per unit width, $D = h + \eta$ is the total depth, $h(x, y)$ is still water depth, $\eta(x, y, t)$ is the surface displacement, $g$ is an acceleration due to gravity, and $m$ is the Manning roughness coefficient.

For rough estimates of the tsunami source parameters, the simplified piston model is used. Here we use the two-parametric (earthquake magnitude and focus depth) model of the tsunami source (Poplavsky *et al.*, 1997). The initial data here is the fault length in the earthquake source $l_0$ related to the earthquake magnitude $\mathrm{M}_0$

$$\log l_0 = 0.5M_0 - 1.8. \tag{4}$$

Dimensions of the tsunami source of the ellipsoidal form are

$$a = \frac{l_0 + 2h_f}{2}, \quad b = h_f, \tag{5}$$

where $a$ and $b$ are the large and small semi-axises of ellipse consequently, and $h_f$ is the depth of the earthquake focus. The height of the sea displacement is found on the empirical formula

$$\log \eta_0 = -4.31 - 4.36 \log h_f + 1.45M_0. \tag{6}$$

Since theses formulas were obtained for the Pacific, the calculation of absolute values of the tsunami heights is not quite correct. But the relation between the tsunami heights in different coastal points should be more realistic, because it depends mainly on the coastal topography and on the very rough characteristics of the tsunami source (in particular, the source orientation). On the open boundaries the well-known condition of the free wave propagation away from domain is used

$$\frac{\partial \eta}{\partial t} + \sqrt{gh}\frac{\partial \eta}{\partial n} = 0, \tag{7}$$

where $n$ is a normal to the open boundary. In the vicinity of the coastline (in the last "sea" point) the vertical wall condition is used

$$\frac{\partial \eta}{\partial n} = 0; \tag{8}$$

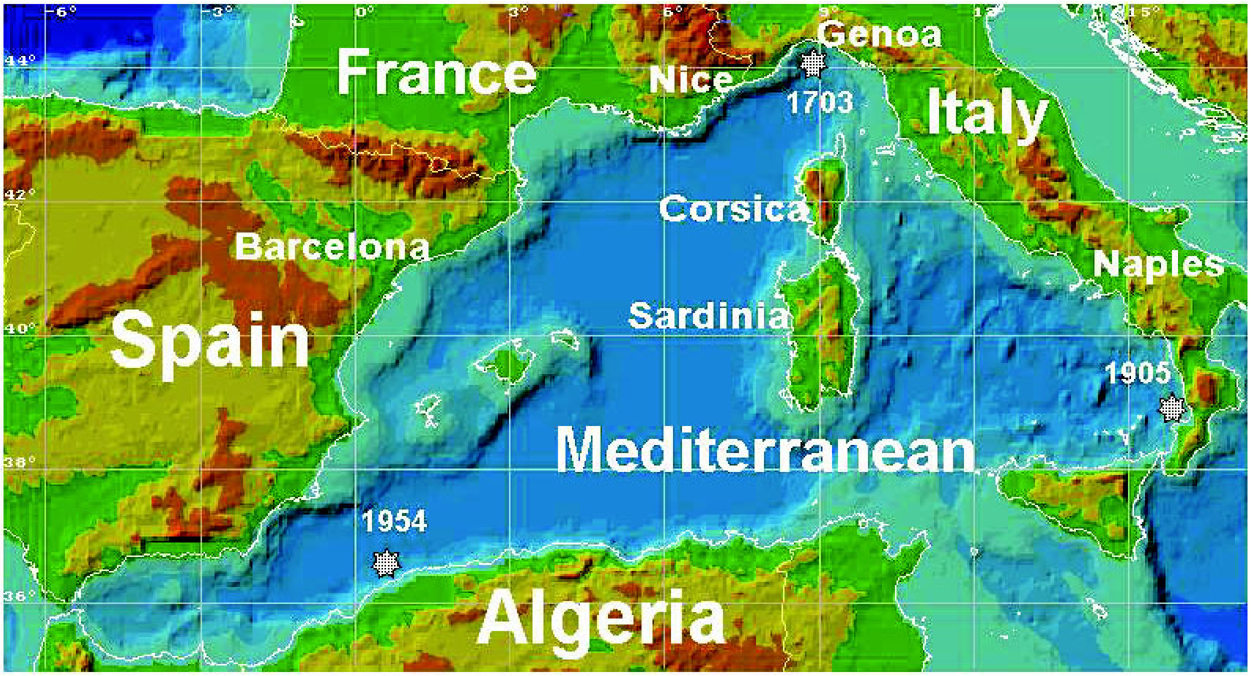


**Figure 2**: Epicenters of earthquakes used for numerical simulation.

as a result, the sea level oscillations along this "wall" are calculated. We assume that the "computed" tide gauge is installed in the last sea point, and its record will be defined as $\eta_w(t)$. The process of the wave run-up is not considered directly. We follow Kaistrenko *et al.* (1999), assuming that the beach is plane and that the wave comes on almost from the onshore direction, and calculate the run-up height with the formula

$$R(t) = \int_0^{t-T} \sqrt{(t-\tau)^2 - T^2} \frac{d^2\eta_w}{d\tau^2} d\tau, \tag{9}$$

where $T$ is a travel time from the last sea point to shore, and $t > T$.

## 4. Synthetic Tsunami Simulations

Taking into account the importance of tsunami generation in the vicinity of Nice–Imperia, four numerical experiments were performed for sources located in this area. The earthquakes in this zone are very shallow, with focal depth of about 10–20 km and can induce significant waves in spite of relative small magnitude (6.2–6.5). The location of the epicenters of computed tsunamis was the same as for historical tsunamis in 1818, 1831, 1854, and 1887. Additionally, three possible epicenters of tsunamis that can reach the French coast are chosen (Fig. 2). The first is the location of the weak earthquake of 2 July 1703 in Genoa (magnitude 3.2). This earthquake generated a local tsunami; in particular, the sea level in the Harbor of Genoa decreased by

1.5–2 m. This example should demonstrate the tsunami propagation from northern Italy to the French coast. The second is the tsunami propagation from southern Italy. Such tsunamis were never registered in France, but taking into account the large seismicity of southern Italy, this area can be considered as a probable place for generation of strong tsunamis. Finally, we considered the tsunami propagation from the Algerian coast, where a strong earthquake occurred on 9 September 1954 (magnitude 6.7). This earthquake induced tsunami waves that were instrumentally recorded on the Spanish coast.

For prognostic modeling we used for all events an earthquake magnitude $M_0 = 6.8$, an earthquake focal depth of 20 km, a northeast orientation of the tsunami source, and a roughness coefficient $m = 0.0012$. According to (5)–(6), the water surface displacement in the tsunami source was 1.5 m and the semi-axis lengths of the ellipsoidal source, 40 and 20 km. This value of the earthquake magnitude corresponds to the mean value for tsunamigenic earthquakes in the whole Mediterranean basin. The chosen source orientation is typical for earthquakes of the northern part of the Ligurian Sea. The parameters have been chosen identically for all simulations to demonstrate the geographical features of tsunami propagation and to compare the possible characteristics of tsunami waves along the coasts. Computed wave elevation was recorded in 7 points for France (Perpignan, Sète, Marseilles, Toulon, Cannes, Nice), including the Island of Corsica (Bastia), and in 4 points for Italy (San Remo, Imperia, Savona, and Genoa). Each "computer" tide gauge is located in the "last" sea point (depth of about 20 m). In this point the assumption of a vertical wall is used and the oscillations of water level on the shoreline are calculated according to (9).

## 5. Discussion of the Results

The results of simulation confirm the observed fact that tsunamis in France have a very local character when the tsunami source is in the vicinity of Nice–Imperia. This is related to the relatively weak magnitudes of possible earthquakes in the vicinity of France. Tsunami records at the nearest point to the earthquake contain, as a rule, a short intense wave train accompanied by a long oscillatory tail. In particular, intense wave groups in San Remo (the event of 1818) have a duration of 1 hr. In Imperia (the event of 1887) the maximal wave was the first wave, and the first three waves were also intense (Fig. 3). Tsunami waves in Cannes–Nice have amplitudes (6–14 cm) two times less than in the nearest points (San Remo or Imperia) for all events. In all other points (or when the epicenter is not too close to the coast) each tsunami record represents the water level oscillations during 10–24 hrs with the characteristic period of tsunami waves ranging from 20 to 30 min in different points. Such slow level oscillations are manifested as the flood (abnormal tides and ebbs), and this corresponds to the descriptions of the historical events. The origin of these oscillations is related to the strong seische oscillations in the Ligurian Sea and with resonance oscillations due to local bottom irregularities. As a result, the characteristic "visible" period of

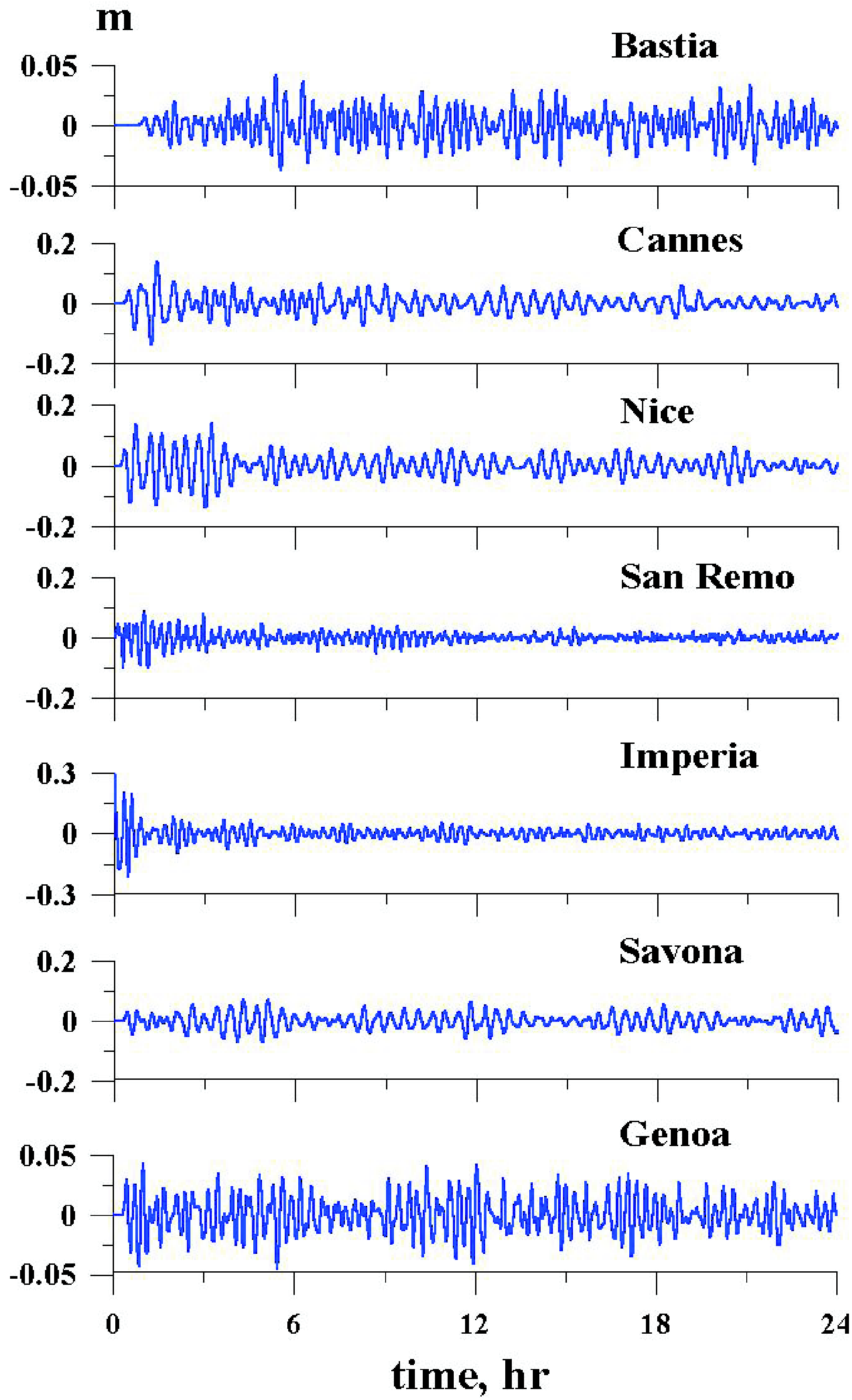


**Figure 3**: Computed tsunami records for the "event" of 1887.

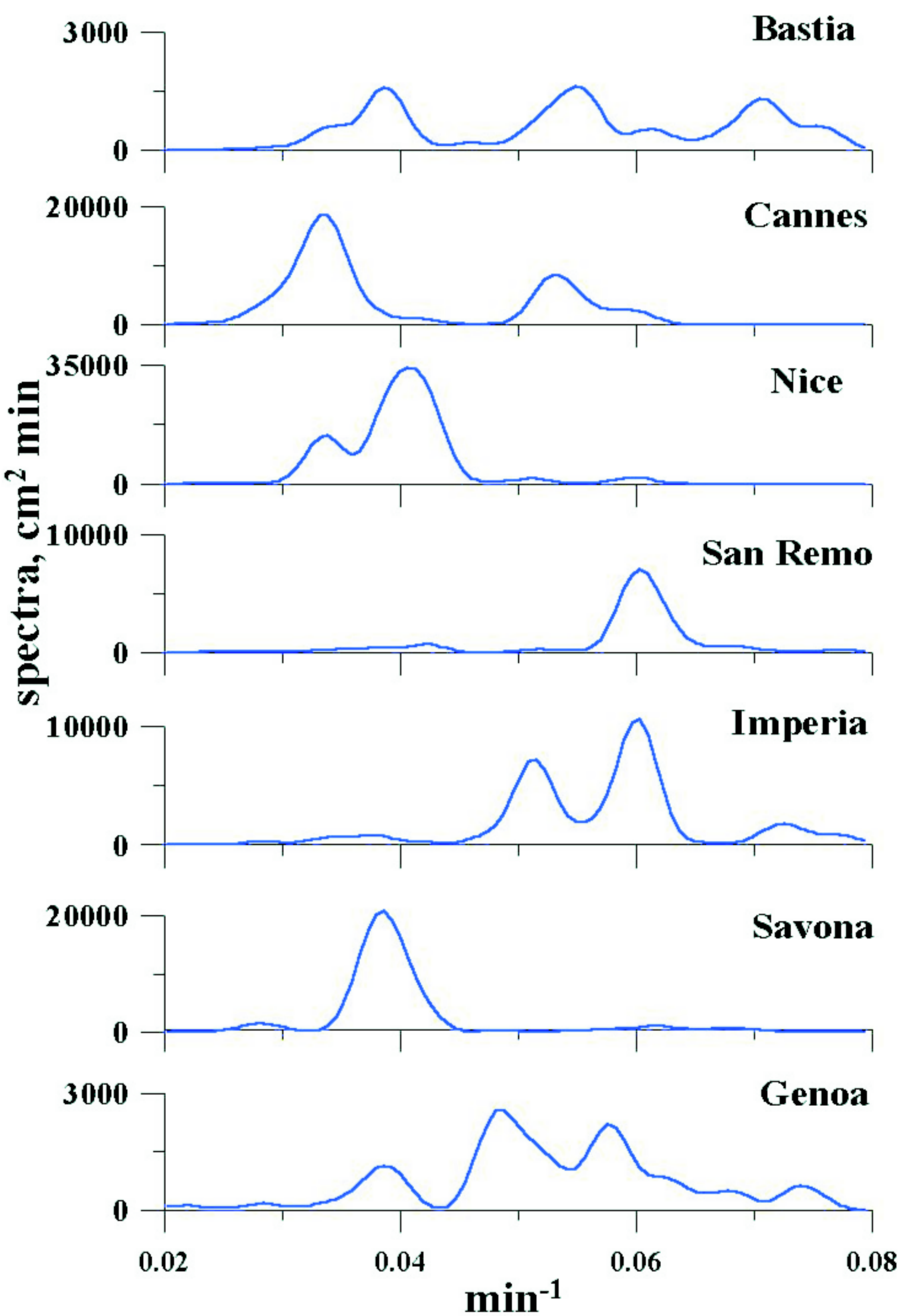


**Figure 4**: Computed spectra for the 1887 event.

waves in Cannes, Nice, and Savona is higher than in San Remo, Imperia, and Genoa for all four events. Results of calculations of the spectra of the 1887 event are presented in Fig. 4. As can be seen, the spectral maximum is varied from point to point and this confirms the complex picture of resonances in the basin of the Ligurian Sea. The low frequency peak (24–30 min) characterized the basin as whole, and is in fact the case for all cities except Imperia and San Remo; the high frequency peak (17–20 min) is strong for Genoa, Imperia, and San Remo. Characteristic amplitude and period of the spectral maxima are in good agreement with observed tide gauge records and the calculations of Eva and Rabinovich (1997). More generally, long duration of tsunami records is characteristic of the French Riviera coasts and this should be accounted for in tsunami warning and forecasting. The character of the wave profiles at the tide gauge point and on the beach is the same. In general, tsunami waves are amplified near the shoreline two to three times for characteristic periods of 20–30 min. It is important to mention that the amplitude of "run-up" approximately equals the amplitude of "run-off". The western part of the Mediterranean coast is protected from these tsunamis by the southern part of the French Rivera. As a result, the tsunami waves at Marseilles, Toulon, Sète, and Perpignan have amplitudes approximately 5–10 times less than in Nice and Cannes.

The impact of far-generated tsunamis was investigated with tsunami sources located at the places of the 1703 Genoa, the 1905 Italy, and the 1954 Algeria earthquakes. In particular, tsunamis generated near Genoa approach to Nice and Cannes with heights (5–7 cm) 5 times less than at Genoa. This simulation, as well as four previous simulations, confirms that tsunamis in the northern part of the Ligurian Sea have a very local character. Tsunamis from the southern part of Italy passed the Ligurian Sea with large attenuation, because Corsica and Sardinia "screen" the French coast. As a result, the wave heights in different points of France have the order of 1–2 cm. Characteristic periods of the computed waves in the western part of the Mediterranean are increased to 1 hr by the effect of short-length wave scattering. The travel time of tsunamis from Italy to the French coast is more than 3 hrs, which is enough for warning and mitigation if an extremely strong tsunami were to be generated near southern Italy. For earthquakes near the coast of Algeria, all points of France are subject to the same conditions from the point of view of wave theory, and wave heights have the same order (1–2 cm) in all points. Approximately 3–6 hrs are needed for tsunamis to approach the French coast. Calculations of the vertical oscillations of the shoreline according to (9) were performed for all variants. As expected, the run-up stage leads to an increase of tsunami height of 2–3 times, and this is a typical value for the mean amplification factor of tsunamis in the coastal zone.

The simplified beach geometry was used to obtain preliminary estimates of the tsunami propagation in the coastal zone of the Ligurian Sea. Besides, tsunami tide gauge records and observed wave heights on the beach during the 1887 Ligurian and 1979 Nice tsunamis reveal that the amplification factor can reach 10 times in specific points. It means that the nearest earthquakes in the vicinity of Cannes–Nice can generate tsunami waves with a maximum run-up of a few meters and induce significant damage on the coast. It also indicates that the resonance properties and the wave climbing process should be related to the specific topographical features of the coastal zone for each city of the Mediterranean coasts.

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