

A semi-empirical approach for tsunami inundation: An application to the coasts of South Italy

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Abstract

Tsunamis in the Mediterranean Sea have been increasingly investigated in the last decades due to past destructive events. We present a novel approach for evaluating tsunami-induced coastal inundation, based on a generalization of Green's law and a chain of intermediate and small-scale numerical simulations. At the intermediate level, simulations with a linear solver are made to identify the coastal distribution of a novel parameter, namely α , condensing all nearshore wave transformations other than shoaling. α represents a proxy for coastal susceptibility to the tsunami impact. Small-scale modelling of coastal flooding performed in the southern Italy on a freely available DTM at the Esaro river estuary (Calabria) yields inundation levels that compare well with those obtained via intermediate-scale modelling, with a saving in computational time of about 41%. This demonstrates the helpfulness of α to "scale" the offshore wave input and reduce the computational effort to evaluate flooding at regional scale.

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Key Points:

- A modelling chain approach for the evaluation of tsunami inundation is described and applied to the coasts of South Italy.
- The method exploits a semi-empirical extension of the classical Green's law to general bathymetries, and dedicated numerical simulations.
- The method allows for transposing computational effort from intermediate to shallow waters.

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Abstract

Tsunamis in the Mediterranean Sea have been increasingly investigated in the last decades due to past destructive events. We present a novel approach for evaluating tsunami-induced coastal inundation, based on a generalization of Green’s law and a chain of intermediate and small-scale numerical simulations. At the intermediate level, simulations with a linear solver are made to identify the coastal distribution of a novel parameter, namely α , condensing all nearshore wave transformations other than shoaling. α represents a proxy for coastal susceptibility to the tsunami impact. Small-scale modelling of coastal flooding performed in the southern Italy on a freely available DTM at the Esaro river estuary (Calabria) yields inundation levels that compare well with those obtained via intermediate-scale modelling, with a saving in computational time of about 41%. This demonstrates the helpfulness of α to “scale” the offshore wave input and reduce the computational effort to evaluate flooding at regional scale.

Plain Language Summary

An interest in studying the consequences of tsunamis has arisen also for the Mediterranean Sea in the last decades. In this manuscript we present a method for the evaluation of potential coastal inundation caused by the impact of tsunamis. The method exploits a chain of numerical simulations of wave propagation to move the tsunami from the source region down to the investigated coasts. The inundation estimate makes use of a simple parameter, named α , devised to encapsulate all the transformation processes the tsunami undergoes in its travel from intermediate waters to the coastline. We apply the method to a portion of the Italian coast (Esaro river estuary, Calabria) with a prototype tsunami event, and we see that inundation levels achieved with faster, small-scale simulations compare well with those obtained with longer, intermediate-scale simulations. The method can be helpful as an implementation in recent tsunami warning systems developed to warn coastal communities on impending tsunami threats.

1 Introduction

The Mediterranean Sea has been subjected since millennia to the action of tsunamis (Ambraseys & Synolakis, 2010; Maramai et al., 2014), yet research interest has seen a boost only recently, in the aftermath of catastrophic events like the Indian Ocean, 2004 (Lay et al., 2005) and Tohoku, 2011 (Fujii et al., 2011; Mori et al., 2011) tsunamis. The high

46 level of seismic activity characterizing the Mediterranean basin and the ubiquity and rich-
47 ness of coastal communities thriving along its coasts spark the need for studies devoted
48 to characterize tsunami propagation within the Mediterranean Sea and, ultimately, their
49 impact on coastal vulnerability. However, recent applications of vulnerability and risk
50 assessments usually take into account important hydrodynamic variables, e.g. sea-level
51 rise, wave height, tide range (Bonaldo et al., 2019; Da Lio & Tosi, 2019; Mattei et al.,
52 2019; Hzami et al., 2021), but disregard the potential contribution of tsunamis (Chaib
53 et al., 2020; Anfuso et al., 2021).

54 The potential coastal risk induced by a tsunami wave is function of its energy, which
55 depends on the processes the tsunami experiences while it approaches the coast, e.g. shoal-
56 ing, refraction, diffraction. Since tsunami waves of similar intensity may present signif-
57 icantly different features when propagating over different bathymetries (Satake, 1988;
58 Madsen et al., 2008), tsunami-seabed interaction is fundamental for a proper modelling
59 of long wave evolution and impact. This consideration has sparked our search for an uni-
60 fied modelling approach to effectively consider bathymetry-related processes in tsunami
61 modelling, while conserving general applicability, scientific soundness and ease of exe-
62 cution.

63 This work presents a methodology for the modelling and prediction of tsunami-induced
64 coastal inundation. At the core of this methodology is a semi-analytical approach, which
65 combines theoretical grounds and nearshore hydrodynamic modelling to encase the ef-
66 fects of all tsunami transformations into a single, easily understandable parameter. To
67 scale the inputs of the procedure from basin-level down to local coasts, a modelling chain
68 concept is applied, as already done in several coastal applications with good results (Federico
69 et al., 2017; Gaeta et al., 2018; Postacchini et al., 2019; Postacchini & Ludeno, 2019).
70 A practical example of the methodology is here applied to a coastal area of the Calabria
71 region, exposed to tsunami waves approaching in an almost perpendicular direction.

72 The modelling chain and the proposed semi-analytical approach are described in
73 Section 2. Results are given in Section 3 and discussed in Section 4, along with conclud-
74 ing remarks.

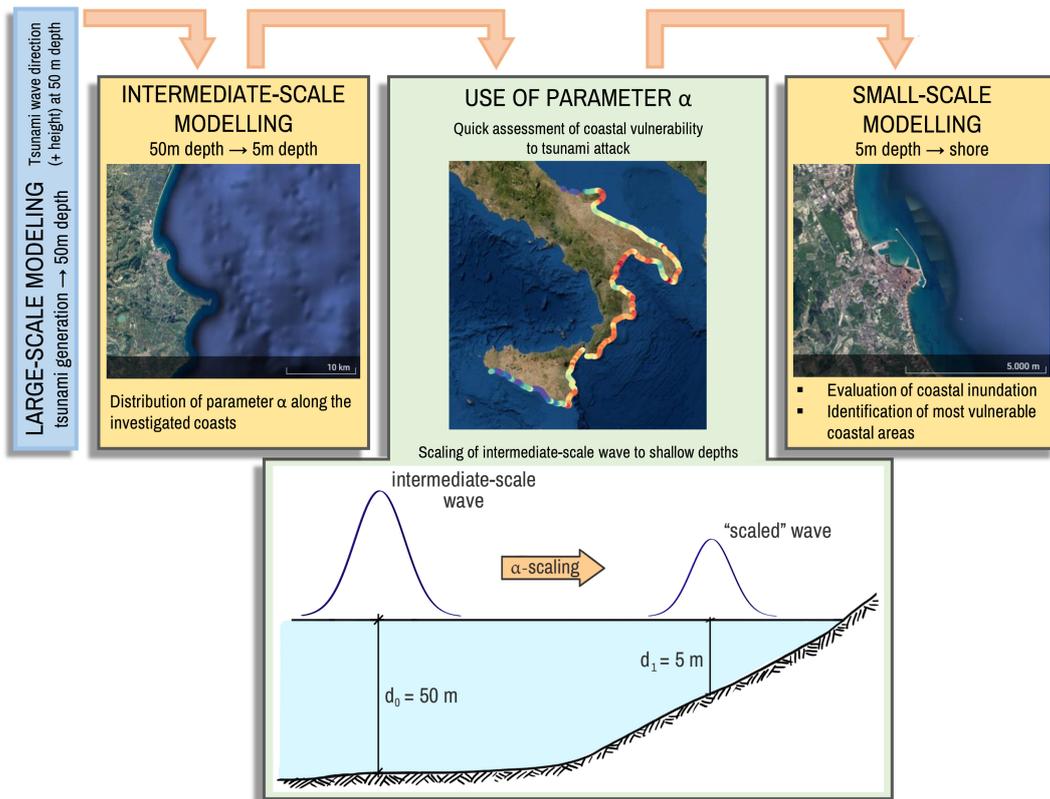


Figure 1. Conceptual scheme of the modelling chain.

2 Methods

2.1 Modelling chain

A conceptual map of the modelling chain is given in Figure 1. The first step of the procedure is tackled with a realistic approach: a tsunami wave is generated at a hypothetical earthquake epicenter located in the Hellenic arc, notoriously the most seismically active region of the Mediterranean Sea (Figure 2). The initial surface displacement then propagates across the Mediterranean basin in a *large-scale modelling*, to infer realistic tsunami front directions at intermediate depths in front of the coasts of interest (an extraction depth of 50 m has been chosen in this application).

In the second step, a separate set of numerical simulations is run (*intermediate-scale modelling*), in which tsunami-like waves are propagated from intermediate waters to the nearshore region in front of the southern Italian coasts (Apulia, Basilicata, Calabria, Sicily; orange outline in Figure 2), which are the most prone to inundation from tsunami waves generated in the Hellenic arc (Maramai et al., 2021). The purpose of intermediate-scale modelling is to gather an along-coast distribution of a parameter (α) which has been devised to serve as a proxy for the several processes (e.g., shoaling, refraction, diffraction) that the modelled tsunami, given a propagating direction derived from the previous large-scale modelling, will undergo during its propagation from intermediate to shallow waters.

After the parameter distribution is obtained, values of α are used in the third step as a “scaling factor” to transport the properties of the tsunami wave from intermediate depths (i.e., the wave shape used as input for the intermediate-scale modelling) up to shallow waters, as described in Section 2.4. The so-scaled wave, which is now assumed to have undergone all the transformation processes represented by α , is used as an initial condition for a *small-scale modelling*, to finally get an estimate of coastal inundation.

2.2 The analytical solution: Green’s law generalization

Lalli et al. (Lalli et al., 2019) have proposed a semi-analytical approach to characterize the transformation process of tsunami-like long waves over general bathymetries: the approach involves a generalization of Green’s law (Dean & Dalrymple, 1991) with

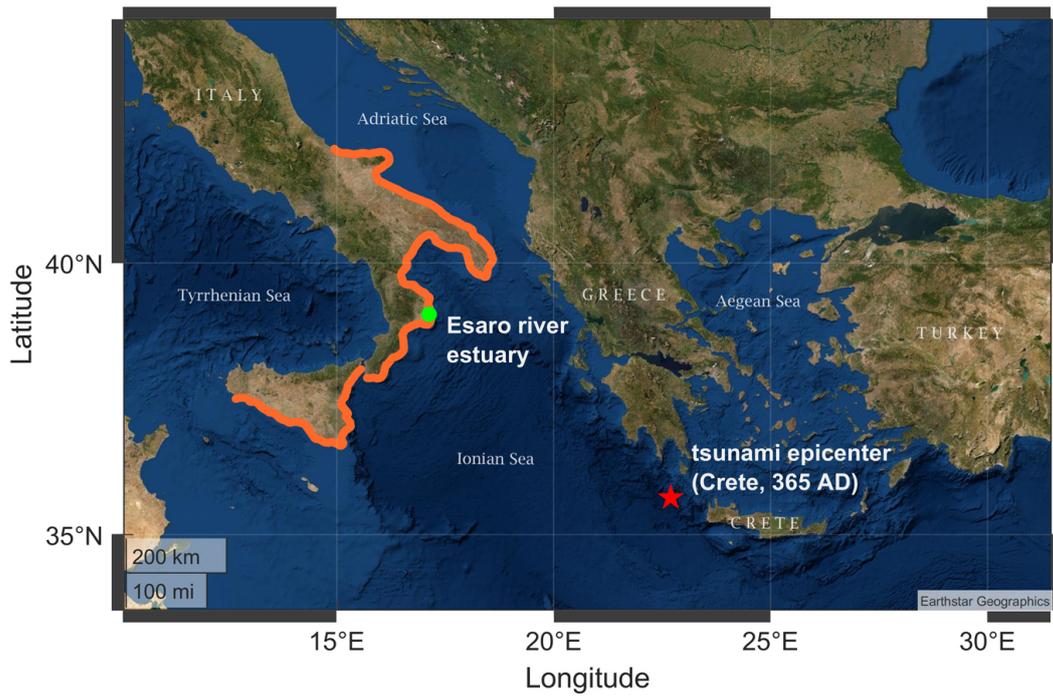


Figure 2. Map of central Mediterranean Sea. The southern Italian coast chosen for the evaluation of α (orange outline), the Esaro river estuary (green circle) and the epicentre of the prototype tsunami event (red star) are shown.

105 a generalizing parameter α :

$$106 \quad H_1 = \alpha H_0 \left(\frac{d_0}{d_1} \right)^{1/4} \quad (1)$$

107 where H_0 and d_0 are the wave height and depth at an offshore location (or in deep wa-
 108 ter), and H_1 and d_1 are the respective values at a location closer to the shore. α is to
 109 be evaluated empirically with the use of suitable numerical simulations of long wave prop-
 110 agation over the complex bathymetry of interest. α is calculated as

$$111 \quad \alpha = \sqrt{\frac{\tilde{\Phi}_1}{\tilde{\Phi}_0}} \quad (2)$$

112 where $\tilde{\Phi}_1$ is the time-cumulative energy flux of the long wave evaluated at any given depth
 113 d_1 , and $\tilde{\Phi}_0$ is the flux at an offshore location d_0 . α can be considered as a proxy of how
 114 much the tsunami energy flux changes as it travels from the deep sea to shallow waters,
 115 by virtue of processes other than pure shoaling. The linear approximation of the spe-
 116 cific energy flux is

$$117 \quad \Phi = gd\eta|V| \quad (3)$$

118 where η is the surface elevation, d is the undisturbed water depth, and V is the depth-
 119 averaged fluid velocity.

120 In a sense, α is similar in concept to the classical refraction coefficient adopted to
 121 model the change in wave height due to refraction. However, it assumes a much broader
 122 meaning when evaluated by numerical modelling, as it also encompasses every contri-
 123 bution to long waves transformation other than shoaling, e.g. reflection, diffraction and
 124 other interactions with natural obstacles and artificial structures.

125 **2.3 The shallow-water model**

126 The α parameter of Equation (2) is numerically evaluated with flux data from nu-
 127 merical simulations of long wave propagation at an intermediate-scale. In the present
 128 application, simulations are performed using the model SASHA (Staggered ANPA SHal-
 129 low wATER; Lalli et al. (2001, 2010)), which solves the shallow water equations with a fi-
 130 nite difference scheme deployed on a staggered Cartesian grid. Such equations represent
 131 the conservation of mass and momentum:

$$132 \quad \frac{\partial \eta}{\partial t} + \frac{\partial U}{\partial x} + \frac{\partial V}{\partial y} = 0, \quad (4)$$

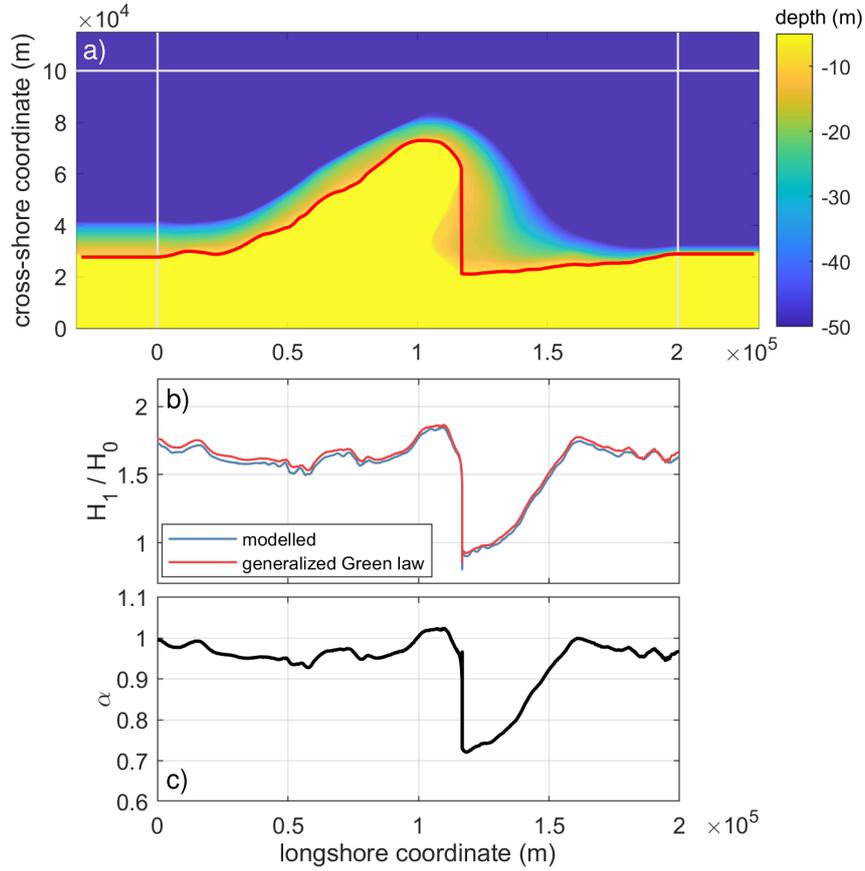


Figure 3. Configuration and output of a typical intermediate-scale simulation with SASHA; **a)** numerical domain. The 5-m isobath (red line) and the limits of the sponge layers (grey lines) are shown; **b)** H_1/H_0 at the 5 m isobath, modelled by SASHA (blue line) and evaluated with Equation (1) (red line); **c)** distribution of modelled α along the 5-m isobath.

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$$\begin{aligned} & \frac{\partial U}{\partial t} + \frac{\partial(U^2/h)}{\partial x} + \frac{\partial(UV/h)}{\partial y} = \\ & = -gh \frac{\partial \eta}{\partial x} + 2 \frac{\partial}{\partial x} \left(\mu h \frac{\partial u}{\partial x} \right) + \frac{\partial}{\partial y} \left[\mu h \left(\frac{\partial v}{\partial x} + \frac{\partial u}{\partial y} \right) \right] - F_u U, \end{aligned} \quad (5)$$

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$$\begin{aligned} & \frac{\partial V}{\partial t} + \frac{\partial(UV/h)}{\partial x} + \frac{\partial(V^2/h)}{\partial y} = \\ & = -gh \frac{\partial \eta}{\partial y} + 2 \frac{\partial}{\partial y} \left(\mu h \frac{\partial v}{\partial y} \right) + \frac{\partial}{\partial x} \left[\mu h \left(\frac{\partial v}{\partial x} + \frac{\partial u}{\partial y} \right) \right] - F_v V. \end{aligned} \quad (6)$$

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The term μ , assumed constant, includes both molecular and eddy viscosity components; F_u and F_v represent friction factors. u and v are depth-averaged horizontal velocities in the x and y directions; h is the total water depth and $U = hu$, $V = hv$. Finally, the total local water depth is approximated with the undisturbed depth ($h \approx d$), so that $U \approx hu$ and $V \approx hv$. Further details can be found in Lalli et al. (2001, 2010, 2019).

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Intermediate-scale simulations in SASHA have been performed for each subdomain into which the southern Italy coastlines has been divided into (Figure 5). An absorbing layer, whose length is equal to half the length of the input prototype wave, has been placed at the landward edge of the modelled region to dissipate the residual wave energy once the long wave has trespassed the 5 m depth isobath. Sponge layers have also been placed at the seaward and lateral sides of the domain to absorb spurious reflected waves.

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On the basis of preliminary tests, solitary waves have been set up at the offshore boundary of each domain and then propagated between 50-m and 5-m depths, bearing in mind that SASHA is a linear model and its results are independent of the wave height imposed at the offshore boundary (Lalli et al., 2019). The nearshore cumulative energy flux $\tilde{\Phi}_1$ is estimated with Equation (3) after the whole wave has traveled through the 5 m isobath, and finally used to evaluate α by means of Equation (2).

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An example of the setting and output of a typical intermediate-scale simulation with SASHA is given in Figure 3 for the Gargano headland (Apulia). Figure 3a shows the bathymetry over which the input wave propagates and the 5-m isobath at which the energy flux is calculated (red line). Figure 3b shows the ratio H_1/H_0 as directly modelled by SASHA (blue line) and as evaluated semi-analytically with the generalized Green's law (red line).

163 A good correspondence of the two curves gives confidence in the method. Values of α
 164 along the 5-m isobath are given in Figure 3c.

165 2.4 Methodology for the assessment of flooding

166 The distribution of α along any given coast is finally employed to “scale” the tsunami
 167 wave properties, i.e. to evaluate its height and length in shallow waters (depth $d_1 = 5$ m),
 168 once the height at intermediate depth ($d_0 = 50$ m) is known. A conceptual scheme of
 169 the scaling process to move intermediate-scale wave input towards shallow depths is given
 170 in the bottom panel of Figure 1.

171 The shallow-water wave height H_1 is first calculated by Equation (1), with α taken
 172 as the mean value $\bar{\alpha}$ along the coastal stretch being investigated:

$$173 H_1 = \bar{\alpha} H_0 \left(\frac{d_0}{d_1} \right)^{1/4}. \quad (7)$$

174 Under the commonly assumed hypothesis that the wave period is conserved between d_0
 175 and d_1 , the shallow water wave length L_1 is then calculated by the definition of the soli-
 176 tary wavenumber provided in Madsen et al. (2008):

$$177 L_1 = \frac{2\pi}{k_1} = 4\pi d_0 \sqrt{\frac{d_1}{3H_0}} \quad (8)$$

178 where k_1 is the wavenumber of the solitary wave in shallow waters. L_1 is therefore taken
 179 as the tsunami wavelength at depth d_1 . A solitary wave characterized by wave height
 180 H_1 and length L_1 has been finally applied as initial condition at depth d_1 , to be used
 181 for the shallow-water simulation for the evaluation of shoreline motion and coastal in-
 182 undation.

183 3 Results

184 3.1 Large-scale modelling: tsunami propagation in the Mediterranean 185 Sea

186 One of the most catastrophic seismic events in the history of the Mediterranean
 187 Sea occurred in 365 A.D. (Stiros, 2001), with epicenter to the West of Crete island, in
 188 the Hellenic arc (the red star in Figure 2). A simple numerical recreation of this tsunami
 189 is considered in our application, to evaluate the global impact of a typical tsunami on
 190 southern Italian coasts and estimate the main approach direction of the long wave front.
 191 Although the main focus of our work is to define a semi-empirical procedure based on

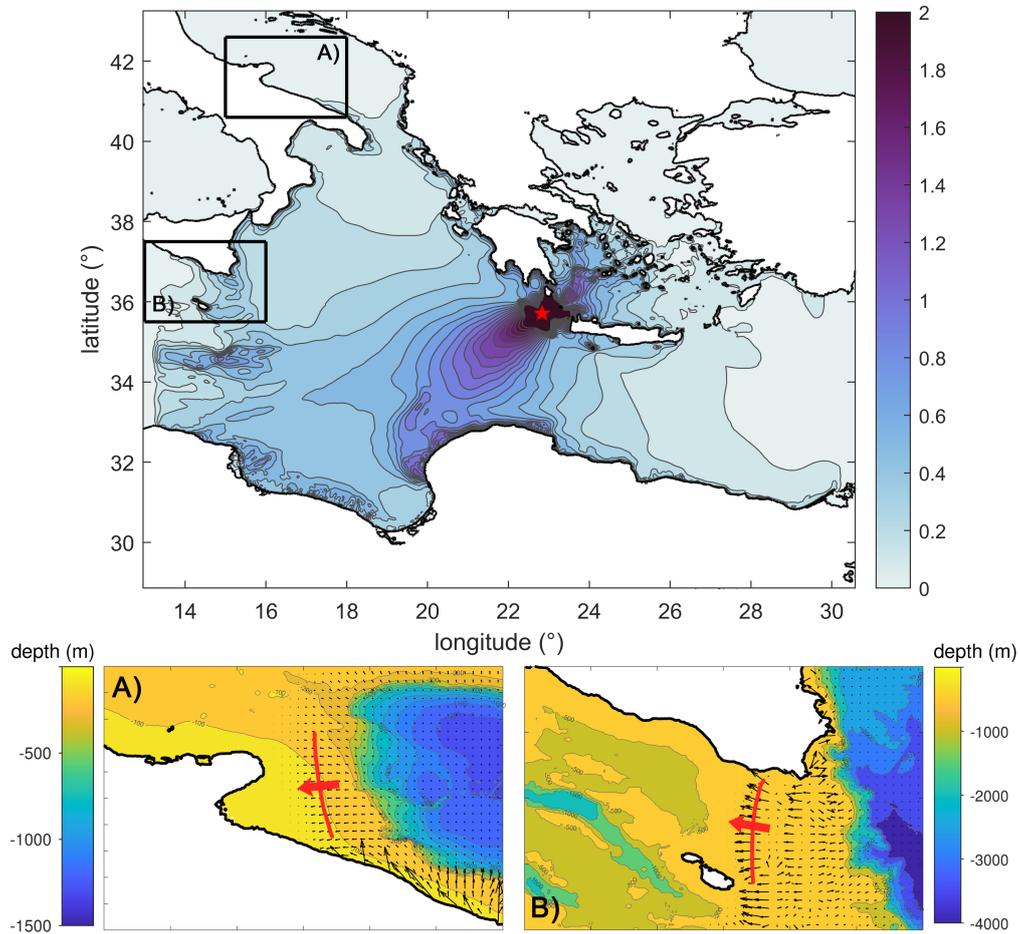


Figure 4. Map of the maximum water level modelled by FUNWAVE-TVD for a prototype tsunami originated from the Hellenic arc, west of Crete Island (red star). The modelled approach directions of the tsunami wave front (red lines and arrows) for Apulia and southern Sicily are highlighted in panels **A)** and **B)**. Black vectors represent the modelled tsunami wave velocity fields.

192 a linear solver and illustrate its application, a preliminary modelling with the renowned
193 nonlinear solver FUNWAVE-TVD (Shi et al., 2012) is made on a basin level.

194 A Gaussian hump has been used to model a prototype tsunami originating in the
195 west Hellenic Arc. The hump has a maximum height of 5 m, while its major axis has
196 an orientation of 45°N to follow the direction of the local underwater fault. The numer-
197 ical grid covering the central part of the Mediterranean Sea has been built using bathy-
198 metric data available at the online platform GEBCO (Weatherall et al., 2015).

199 Figure 4 illustrates the maximum modelled water elevation in the central Mediter-
200 ranean Sea. The output of such typical scenario has been used to identify the propaga-
201 tion direction of the tsunami wave in front of the coasts of interest, at 50-m water depth,
202 i.e. the offshore location at which the semi-analytical approach is applied. Figure 4 also
203 shows that portions of the Apulian and Sicilian coasts experienced the most angled waves,
204 i.e. respectively, inclined of $\sim 60^\circ$ with respect to the direction orthogonal to the coast
205 and almost parallel to the coast (Figure 4A and B).

206 **3.2 Intermediate-scale modelling: α distribution along the southern Ital-** 207 **ian coasts**

208 The parameter α has been computed along the Italian coasts by subdividing the
209 interested coastlines into a number of domains of variable cross-shore and longshore sizes,
210 generally in the order of 100–200 km (Figure 5a–b), to allow for a more detailed char-
211 acterization of each coastal region. All grid sizes in both directions are set at 150 m. The
212 bathymetries have been smoothed with a median filter to remove occasional spikes and
213 ensure a smooth wave transformation.

214 The α distribution for the investigated coasts is given in Figure 5c–d. The values
215 of α have been evaluated from the outcome of intermediate-scale simulations with SASHA:
216 small and high values of α are indicative of low tsunami impact (small residual energy
217 flux at 5 m depth) and high tsunami impact (high residual energy flux at 5 m depth),
218 respectively.

219 The smallest values of α are observed in areas that are less exposed to the action
220 of a tsunami at a realistic attack angle, due to their favourable geographical location.
221 The coast north of the Apulia Region (Figure 5c) is characterized by small values of α

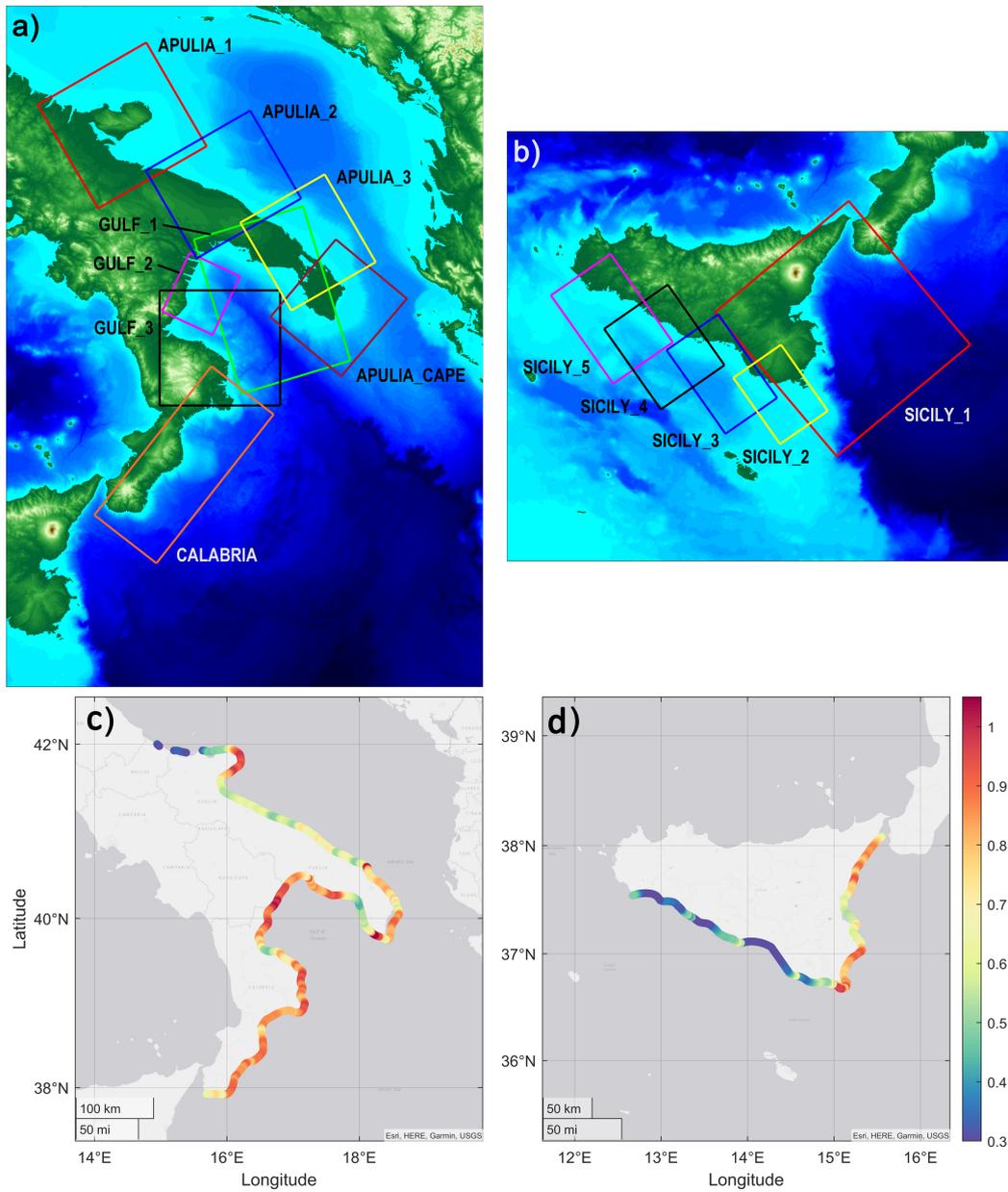


Figure 5. Domains used for the SASHA simulation campaign and distribution of the parameter α evaluated through the semi-analytical approach for **a, c)** peninsular Italy (Apulia, Basilicata, Calabria), and **b, d)** Sicily.

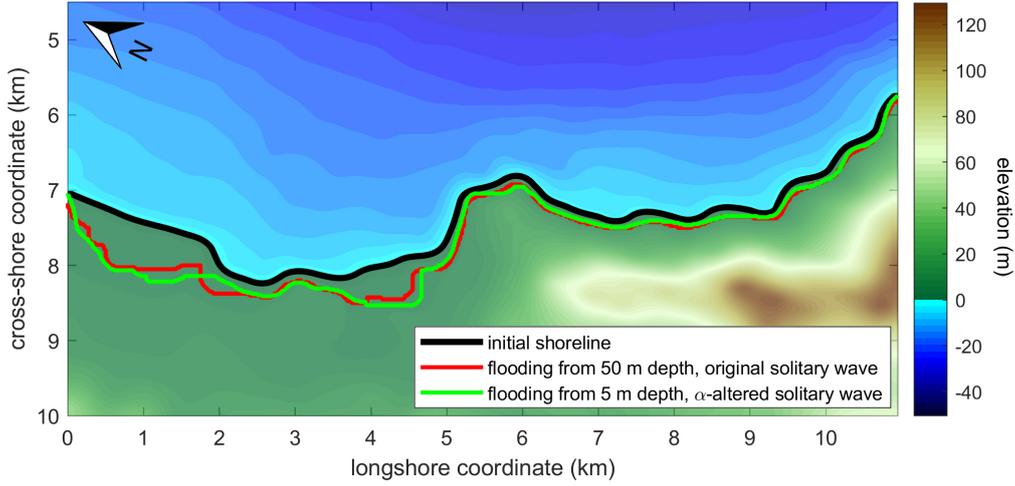


Figure 6. Area around the Esaro River estuary, used as numerical domain for the small-scale modelling, and comparison of shorelines simulated with the tested approaches: initial shoreline (black line), maximum inundation of a 2-m solitary wave at a 50-m depth (red line), maximum inundation of the α -scaled solitary wave (3.03 m wave height) imposed at 5-m depth (green line).

222 (< 0.4), as it is protected by the Gargano Promontory, which is in turn much more sus-
 223 ceptible to tsunami energy ($\alpha > 1$). A similar behavior is observed in Sicily (Figure 5d),
 224 whose southern and western coasts ($\alpha < 0.4$) are more protected than the eastern coasts
 225 ($\alpha \approx 1$). The whole Calabria coast is highly impacted by the tsunami wave, with α os-
 226 cillating around 1 almost everywhere, with the most exposed area being that of the Taranto
 227 Gulf. Less impacted is the Adriatic Apulia coast, with $\alpha \approx (0.5-0.6)$ on average, while
 228 the southernmost part of Apulia is highly exposed ($\alpha \approx 1$).

229 **3.3 Small-scale modelling: nearshore propagation and flooding**

230 As an illustrative example, α evaluated in the intermediate-scale modelling cam-
 231 paign and pictured in Figure 5c-d are exploited to model flooding levels in the coastal
 232 region surrounding the Esaro River estuary (Calabria). The chosen location is charac-
 233 terized by an urbanized setting with industrial, residential and recreational areas, and
 234 is thus representative of a typical Italian coastal environment.

235 Shallow-water, small-scale coastal modelling is performed using FUNWAVE-TVD
 236 on a computational domain with a maximum offshore depth of 5 m (i.e. the depth at
 237 which α is evaluated). Now, the definition of wave input for this simulation implements

238 the concept of α as a proxy of seabed-induced effects; that is, the wave form used as in-
239 put for intermediate-scale modelling (50 m) is “scaled” through α to reduce it at 5-m
240 depth. The “scaled” wave input is then applied as an initial condition of water surface
241 displacement at a water depth 5 m and used to evaluate coastal flooding. The scaling
242 is performed with the formulas given in Section 2.4. With the use of α , all bathymetry-
243 related dynamics influencing the solitary wave height (shoaling, refraction, diffraction)
244 are included when transporting wave data from intermediate to shallow waters. This ap-
245 plication allows us to show that a good representation of tsunami-induced inundation
246 can also be achieved with input data from simpler, linear tools and semi-analytical con-
247 cepts.

248 In the example we assume that the tsunami height at $d_0 = 50$ m is $H_0 = 2$ m.
249 Provided that the mean value of α along the considered coast is 0.853, the “scaled” in-
250 put wave to be imposed at $d_1 = 5$ m depth would have a wave height $H_1 = 3.03$ m
251 and a wavelength $L_1 = 573.57$ m.

252 We make a comparison of coastal flooding levels obtained with the two previously
253 mentioned approaches: (i) intermediate-scale simulation on a 25×25 m grid with a 2-
254 m solitary wave at offshore depth 50 m, and (ii) small-scale simulation on a 15×15 m
255 grid with a 3.03-m “scaled” wave at offshore depth 5 m. Figure 6 shows maximum shore-
256 line motions for both approaches. The two modelled shorelines are overall in good agree-
257 ment, lending support to a fruitful use of α as a tool to move modelling efforts towards
258 smaller scales once offshore tsunami data are known, by either observation or previous
259 modelling. In this application, the small-scale simulation achieved a reduction of about
260 41% in computational time with respect to the intermediate-scale simulation.

261 4 Discussion and Conclusions

262 The method and application here proposed have shown that once the α parame-
263 ter is defined and available in a specific coastal area, coastal inundation can be evalu-
264 ated by running only a small-scale simulation over the coast of interest, while pre-defined
265 information (e.g., wave direction and α) are known beforehand to speed up the whole
266 forecasting process. The method allows for the down-scaling of computational effort to-
267 wards small regional scales once information from a relatively coarser basin-scale sim-
268 ulation is available. This help complying with the need of fast (typically, within a few

269 minutes), yet reliable deterministic first estimates of tsunami impact (Selva et al., 2021)
270 only in the region of interest.

271 The modelling chain has its starting point in the definition of a prototypical tsunami
272 based on a real, catastrophic event. In this regard, the procedure proposed here is sim-
273 ilar to a worst-case plausible scenario. The analysis of a limited number or even single
274 scenarios may be put in tandem with previous probabilistic hazard assessments (like those
275 described in Tonini et al. (2021) and Selva et al. (2021)) in the perspective of narrow-
276 ing tsunami variability down to a range of most probable parameters.

277 The method is also valuable when precise forecasting of flooding is needed. In fact,
278 underestimation of tsunami features may lead to fatal missed alarms, as occurred dur-
279 ing the 2011 Tohoku tsunami event, when the tsunami height was initially underestimated,
280 and so the inundated coastal area. This led to a number of casualties much larger than
281 those that could have been suffered with a more accurate forecasting (Makinoshima et
282 al., 2021).

283 It is worthwhile to notice that the semi-empirical implementation of the Green’s
284 law explicitly accounts for the effects of the bathymetry over the deformation of the wave
285 front and, eventually, over tsunami impact. Bathymetry effects are inherently neglected
286 in non-probabilistic procedures for tsunami-related alert states like decision matrices (Selva
287 et al., 2021), and circumvented by end-to-end forecasting methods like neural network-
288 ing (Makinoshima et al., 2021). On the other hand, probabilistic methods deal with the
289 unknown effects of bathymetry only with varying uncertainty bounds on forecast results (Selva
290 et al., 2021).

291 The methodology could be further improved by tackling other sources of uncertainty,
292 like fault orientation and the subsequent main direction of propagation (Selva et al., 2021).
293 With additional work on code optimization and automation, the procedure could also
294 be applied to sources with general initial surface displacements, possibly evaluated as
295 a function of earthquake parameters.

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304 6 Open Research

305 A dataset including input and output data for the presented simulations is avail-
 306 able at the Zenodo repository referenced in Melito et al. (2022). Version 3.6 of the soft-
 307 ware Funwave has been used for hydrodynamic modelling; the model is in the public do-
 308 main and can be downloaded at the following page: [https://github.com/fengyanshi/
 309 FUNWAVE-TVD/releases/tag/Version_3.6](https://github.com/fengyanshi/FUNWAVE-TVD/releases/tag/Version_3.6). Bathymetries are freely available at the GEBCO
 310 platform: <https://www.gebco.net>.

311 References

- 312 Ambraseys, N., & Synolakis, C. (2010). Tsunami catalogs for the Eastern Mediter-
 313 ranean, revisited. *Journal of Earthquake Engineering*, *14*(3), 309–330.
- 314 Anfuso, G., Postacchini, M., Di Luccio, D., & Benassai, G. (2021). Coastal sensitiv-
 315 ity/vulnerability characterization and adaptation strategies: a review. *Journal
 316 of Marine Science and Engineering*, *9*(1), 72.
- 317 Bonaldo, D., Antonioli, F., Archetti, R., Bezzi, A., Correggiari, A., Davolio, S., ...
 318 others (2019). Integrating multidisciplinary instruments for assessing coastal
 319 vulnerability to erosion and sea level rise: Lessons and challenges from the
 320 Adriatic Sea, Italy. *Journal of Coastal Conservation*, *23*(1), 19–37.
- 321 Chaib, W., Guerfi, M., & Hemdane, Y. (2020). Evaluation of coastal vulnerabil-
 322 ity and exposure to erosion and submersion risks in Bou Ismail Bay (Algeria)
 323 using the coastal risk index (CRI). *Arabian Journal of Geosciences*, *13*(11),
 324 1–18.
- 325 Da Lio, C., & Tosi, L. (2019). Vulnerability to relative sea-level rise in the Po river
 326 delta (Italy). *Estuarine, Coastal and Shelf Science*, *228*, 106379.
- 327 Dean, R. G., & Dalrymple, R. A. (1991). *Water Wave Mechanics for Engineers and
 328 Scientists* (Vol. 2). World Scientific. doi: 10.1142/1232
- 329 Federico, I., Pinardi, N., Coppini, G., Oddo, P., Lecci, R., & Mossa, M. (2017).
 330 Coastal ocean forecasting with an unstructured grid model in the southern

- 331 Adriatic and northern Ionian seas. *Natural Hazards and Earth System Sci-*
332 *ences*, 17(1), 45–59.
- 333 Fujii, Y., Satake, K., Sakai, S., Shinohara, M., & Kanazawa, T. (2011). Tsunami
334 source of the 2011 off the Pacific coast of Tohoku Earthquake. *Earth Planets*
335 *Space*, 63(7), 815–820. doi: 10.5047/eps.2011.06.010
- 336 Gaeta, M. G., Bonaldo, D., Samaras, A. G., Carniel, S., & Archetti, R. (2018). Cou-
337 pled wave-2d hydrodynamics modeling at the Reno river mouth (Italy) under
338 climate change scenarios. *Water*, 10(10), 1380.
- 339 Hzami, A., Heggy, E., Amrouni, O., Mahé, G., Maanan, M., & Abdeljaouad, S.
340 (2021). Alarming coastal vulnerability of the deltaic and sandy beaches of
341 North Africa. *Scientific reports*, 11(1), 1–15.
- 342 Lalli, F., Berti, D., Miozzi, M., Miscione, F., Porfidia, B., Serva, L., . . . others
343 (2001). Analysis of breakwater-induced environmental effects at Pescara
344 (Adriatic Sea, Italy) channel-harbor. In *The eleventh international offshore*
345 *and polar engineering conference*.
- 346 Lalli, F., Bruschi, A., Lama, R., Liberti, L., Mandrone, S., & Pesarino, V. (2010).
347 Coanda effect in coastal flows. *Coastal Eng.*, 57(3), 278–289.
- 348 Lalli, F., Postacchini, M., & Brocchini, M. (2019). Long waves approaching the
349 coast: Green’s law generalization. *J. Ocean Eng. Marine Energy*, 5(4), 385–
350 402. doi: 10.1007/s40722-019-00152-9
- 351 Lay, T., Kanamori, H., Ammon, C. J., Nettles, M., Ward, S. N., Aster, R. C., . . .
352 others (2005). The great Sumatra-Andaman earthquake of 26 December 2004.
353 *Science*, 308(5725), 1127–1133. doi: 10.1126/science.1112250
- 354 Madsen, P. A., Fuhrman, D. R., & Schäffer, H. A. (2008). On the solitary wave
355 paradigm for tsunamis. *Journal of Geophysical Research: Oceans*, 113(C12).
- 356 Makinoshima, F., Oishi, Y., Yamazaki, T., Furumura, T., & Imamura, F. (2021).
357 Early forecasting of tsunami inundation from tsunami and geodetic observation
358 data with convolutional neural networks. *Nature Communications*, 12(1),
359 1–10.
- 360 Maramai, A., Brizuela, B., & Graziani, L. (2014). The Euro-Mediterranean tsunami
361 catalogue. *Ann. Geophys.-Italy*, 57(4). doi: 10.4401/ag-6437
- 362 Maramai, A., Graziani, L., & Brizuela, B. (2021). Italian Tsunami Effects Database
363 (ITED): The first database of tsunami effects observed along the Italian coasts.

- 364 *Front. Earth Sci.*, 9, 137. doi: 10.3389/feart.2021.596044
- 365 Mattei, G., Rizzo, A., Anfuso, G., Aucelli, P., & Gracia, F. (2019). A tool for eval-
366 uating the archaeological heritage vulnerability to coastal processes: The case
367 study of Naples Gulf (southern Italy). *Ocean & Coastal Management*, 179,
368 104876.
- 369 Melito, L., Lalli, F., Postacchini, M., & Brocchini, M. (2022). *Simulation data for a*
370 *semi-empirical approach for tsunami inundation in South Italy* [dataset]. Zen-
371 odo. doi: 10.5281/zenodo.6249936
- 372 Mori, N., Takahashi, T., Yasuda, T., & Yanagisawa, H. (2011). Survey of 2011
373 tohoku earthquake tsunami inundation and run-up. *Geophysical Research Let-*
374 *ters*, 38(7).
- 375 Postacchini, M., Lalli, F., Memmola, F., Bruschi, A., Bellafiore, D., Lisi, I., . . .
376 Brocchini, M. (2019). A model chain approach for coastal inundation: Ap-
377 plication to the bay of Alghero. *Estuarine, Coastal and Shelf Science*, 219,
378 56–70.
- 379 Postacchini, M., & Ludeno, G. (2019). Combining numerical simulations and nor-
380 malized scalar product strategy: A new tool for predicting beach inundation.
381 *Journal of Marine Science and Engineering*, 7(9), 325.
- 382 Satake, K. (1988). Effects of bathymetry on tsunami propagation: Application of ray
383 tracing to tsunamis. *Pure and Applied Geophysics*, 126(1), 27–36.
- 384 Selva, J., Lorito, S., Volpe, M., Romano, F., Tonini, R., Perfetti, P., . . . others
385 (2021). Probabilistic tsunami forecasting for early warning. *Nature Communi-*
386 *cations*, 12(1), 1–14.
- 387 Shi, F., Kirby, J. T., Harris, J. C., Geiman, J. D., & Grilli, S. T. (2012). A high-
388 order adaptive time-stepping TVD solver for Boussinesq modeling of breaking
389 waves and coastal inundation. *Ocean Modelling*, 43, 36–51.
- 390 Stiros, S. C. (2001). The AD 365 Crete earthquake and possible seismic cluster-
391 ing during the fourth to sixth centuries AD in the Eastern Mediterranean: a
392 review of historical and archaeological data. *Journal of Structural Geology*,
393 23(2-3), 545–562.
- 394 Tonini, R., Di Manna, P., Lorito, S., Selva, J., Volpe, M., Romano, F., . . . Vittori,
395 E. (2021). Testing Tsunami Inundation Maps for Evacuation Planning in Italy.
396 *Frontiers in Earth Science*, 9. doi: 10.3389/feart.2021.628061

397 Weatherall, P., Marks, K. M., Jakobsson, M., Schmitt, T., Tani, S., Arndt, J. E., . . .
398 Wigley, R. (2015). A new digital bathymetric model of the world's oceans.
399 *Earth and Space Science*, 2(8), 331–345.