Towards the Adriatic Meteotsunami Early Warning System: Deterministic and Stochastic Modelling Strategy

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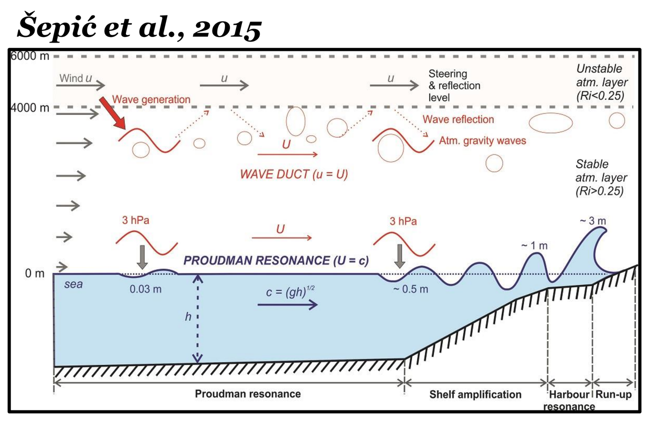
1. Motivation of Research: MESSI Project

Meteorological Tsunamis (Meteotsunamis)

Meteotsunamis are hazardous **long ocean waves** (tsunami-like) generated by **atmospheric conditions** such as pressure jumps, atmospheric gravity waves, frontal passages, squalls, etc.

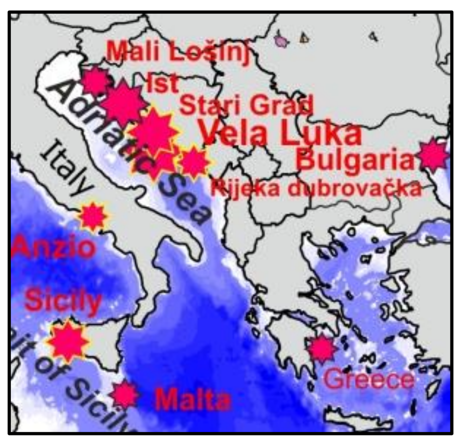
The **generation** of **meteotsunamis** depends on **resonant transfer of energy** (i.e. Proudman and harbour) from the atmosphere to the sea.

Šepić et al., 2015



Historical Meteotsunamis along Croatian Coastline

Meteotsunamis Recorded along the Croatian Coastline

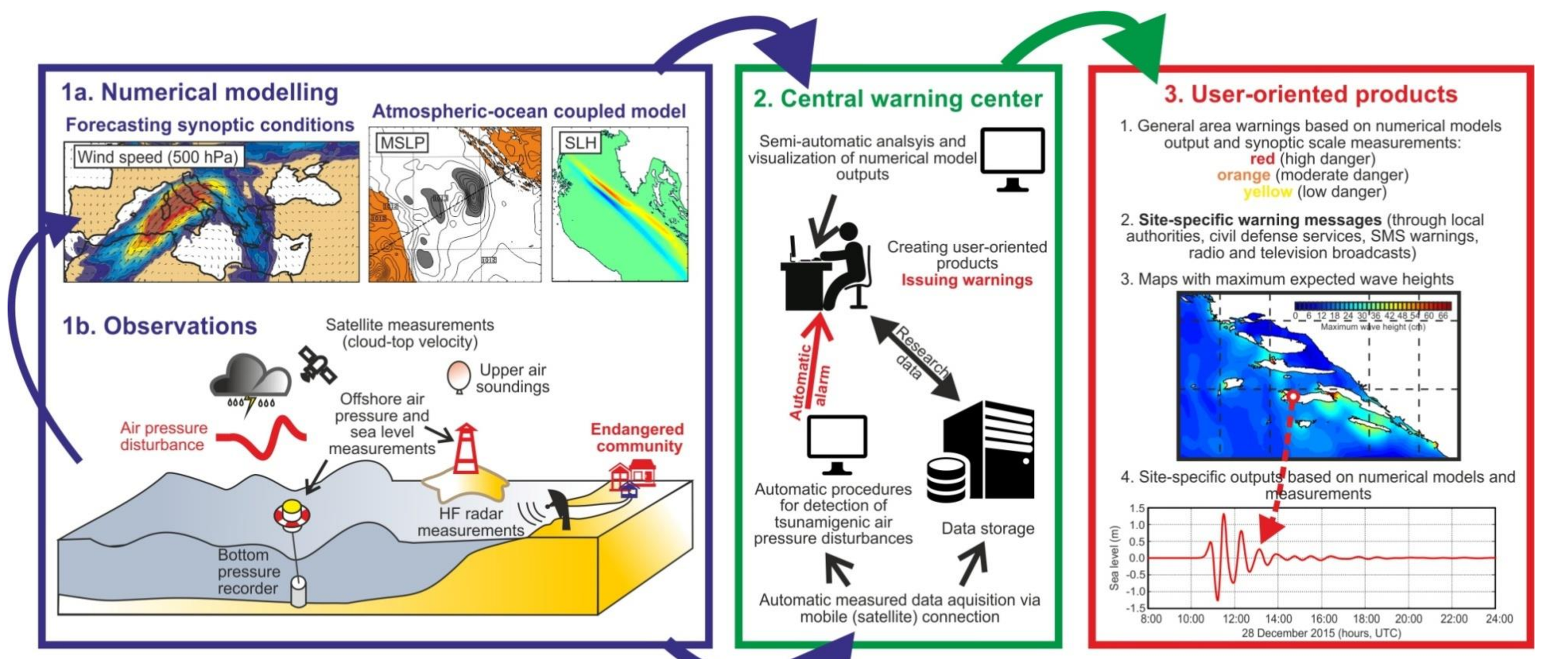


Location	Date	Height (m)	Onset time (LT)	Duration of the event (h)	Period of oscillations (min)	Quality indicator
Korčula	27/08/1966	1.65	16:00	2	15	2
Vela Luka	10/02/1972	2	11:00	5.5		2
Vela Luka	21/08/1977	4				2
Vela Luka	20/09/1977	4	22:00	4.5	25	2
Vela Luka	21/06/1978	6	5:15			
Vela Luka	06/07/1978	2				2
Vela Luka	12/02/1979	2	13:00	6		2
Stari Grad	10/07/1980	2.5	5:00		40	2
Ist	05/10/1984	4				2
Stari Grad	27/06/2003	3.5	6:00			5
Ist	22/08/2007	4	17:30	1	10	4
Mali Lošinj	15/08/2008	3.5	18:50	1	20	3
Stari Grad	19/02/2010	3				3
Vela Luka	25/06/2014	3	06:00			5

The **strongest Croatian event**, the Great Vela Luka Flood of 21 June 1978, is likely the **strongest meteotsunami wave** ever recorded (**~6m** height and **20min** period).
A large number of meteotsunamis have been observed along the Croatian Coastline between 1966 and nowadays and an **online catalogue** have been built over the years (Šepić and Orlić).
The June 2014 event is of particular interest for this study as pressure and sea level measurements were recorded at more than 60 locations.

Messi Project: Meteotsunami Early Warning System

The aim of the MESSI project is to build a **meteotsunami warning system** based on **real-time measurements**, **operational atmosphere** and **ocean modelling** and real time **decision-making process**.
The goal of this study is to design and test the modelling component of the project.

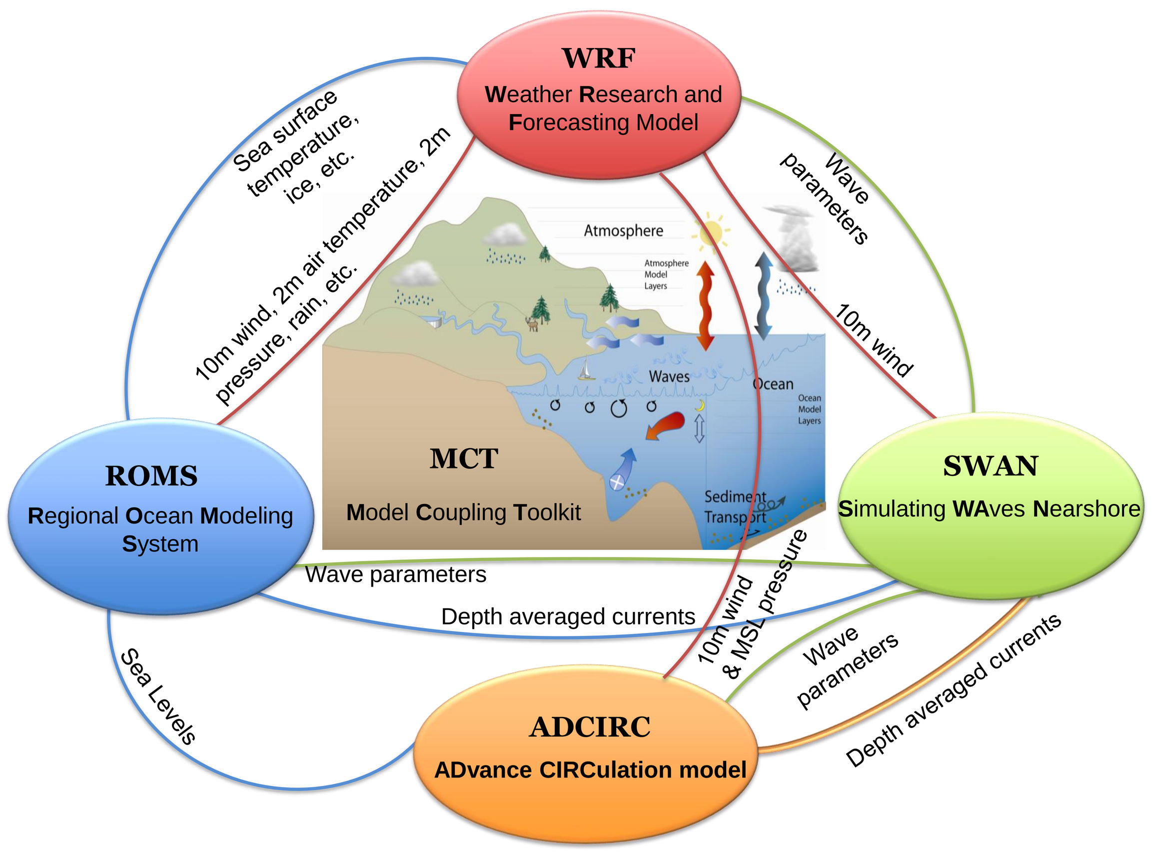


Vilibić et al., 2016 (Frontiers)

2. Modelling Strategy

Coupled COAWST and ADCIRC Models

The **C**oupled – **O**cean – **A**tmosphere – **W**ave – **S**ediment **T**ransport (COAWST) Modeling System is tailored to investigate coastal processes of the atmosphere, ocean, waves, and coastal environment.
The **AD**vanced **CIRC**ulation Model is a highly developed computer program using finite element method for space discretization in order to allow a better representation of the coastline and a higher resolution of nearshore areas.

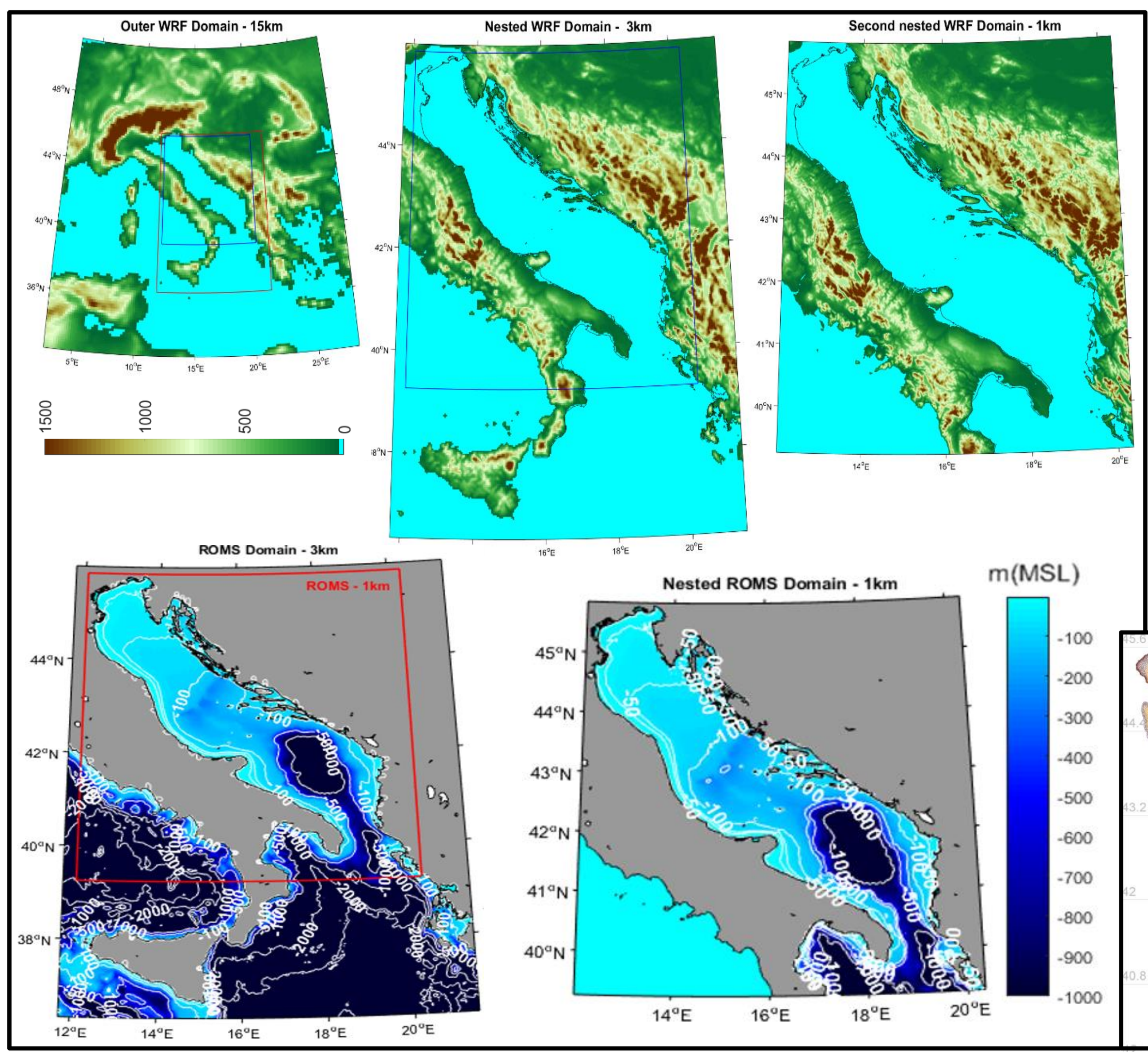


Modelling Strategy

To reproduce and forecast meteotsunamis it is required:
- to model the **atmospheric pressure** with an **extremely high temporal resolution**
- to **represent accurately** the **coastline** as well as the **bathymetry** of the channels

The fully coupled COAWST system generates *a high resolution atmospheric input (i.e. 1 min) used on the fly to force the 3D ROMS model.*

*However the structured ROMS model can not represent properly the geomorphology of the complex coastline of Croatia. It is **necessary** to use an **unstructured** model such as **ADCIRC** to model the tsunami-like waves.*



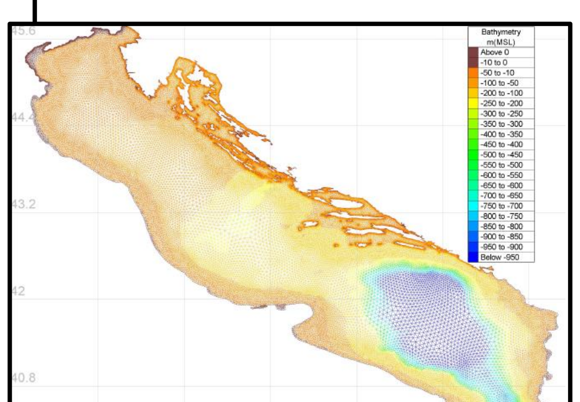
Domains and Forcing

TOPOGRAPHY: DTM representing the complex Croatian geomorphology.

WRF: 1 domain of 15km forced with the 6 hourly ERAI data and 2 nested domains of 3km and 1km resolution.

ROMS: 2 domains of 3km and 1km resolution forced by the daily MEDSEA data and 45 rivers.

ADCIRC: resolution up to 15m



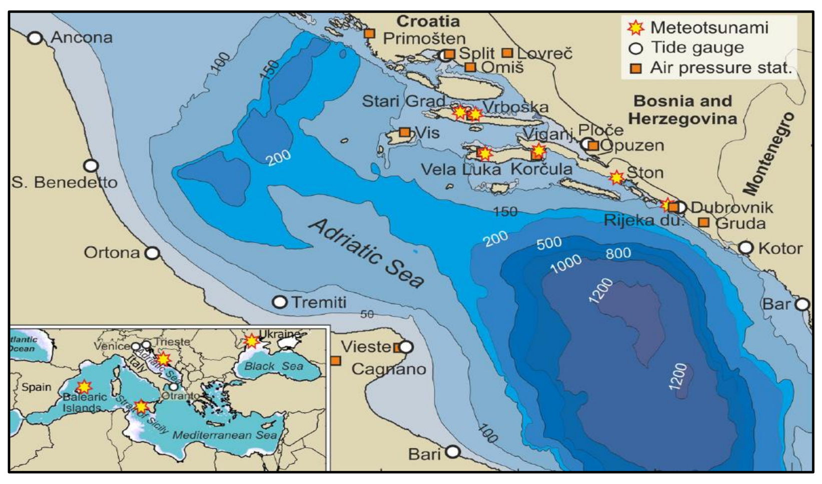
ADCIRC Mesh – up to 15m

3. Meteotsunami of June 2014

Measurements

Between the **25th and 26th of June 2014** the eastern coast of the Adriatic Sea was hit by **two tsunami-like waves** which were observed both in the atmosphere and in the ocean at various locations.

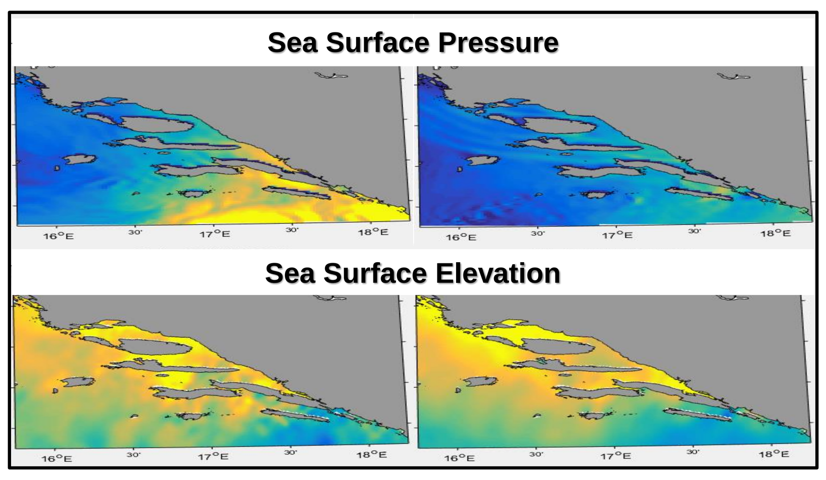
Both Atmospheric Pressure and Sea Level were recorded during the meteotsunami of June 2014.
The available measurements are as follow:
(1) 45 Meteo Stations located in **Croatia** – including amateur measurements
(2) 6 Sea Level Stations in **Italy**
(3) 3 Sea Level Stations in **Croatia**
(4) 2 Sea Level Stations in **Montenegro**



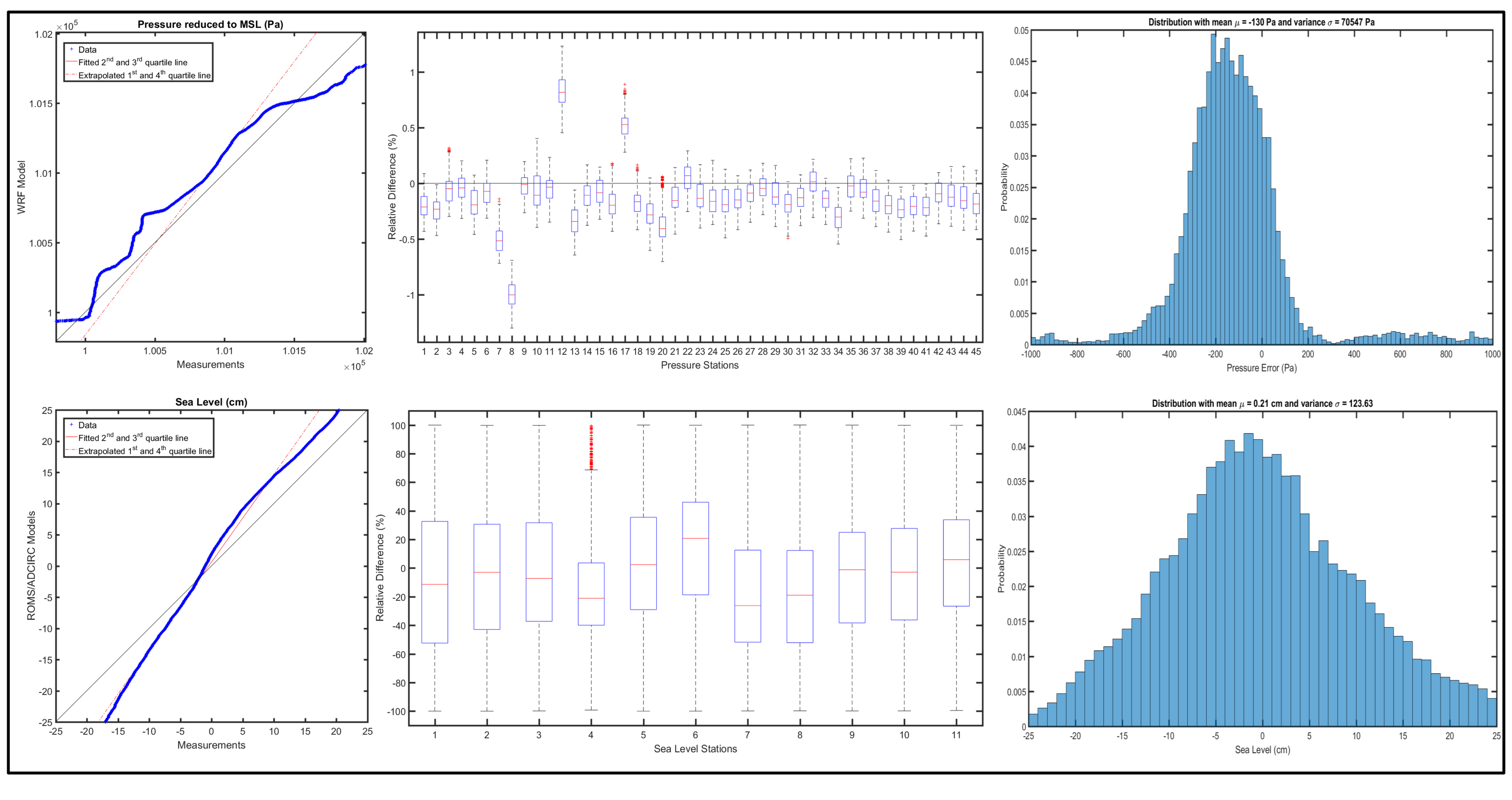
Šepić et al., 2016 (PAGEOPH)

Location	Max. Measured Height (cm)			Max. Modeled Height (cm)		
	Date	Mes.	Mod.	Date	Mod.	Mes.
Ancona	25-Jun 18:31	34.8	28.5	25-Jun 20:10	41.7	27.0
St Benedetto	26-Jun 15:30	45.1	28.6	26-Jun 16:40	34.0	27.9
Ortona	25-Jun 16:21	55.9	25.2	25-Jun 16:45	43.7	49.0
Tremiti	25-Jun 14:56	27.8	31.3	26-Jun 15:52	33.0	23.6
Vieste	26-Jun 17:07	42.1	11.5	25-Jun 15:04	36.1	27.9
Otranto	26-Jun 16:20	36.6	8.5	26-Jun 02:31	14.6	6.26
Split	25-Jun 16:07	38.1	41.1	26-Jun 15:18	48.9	26.6
Ploće	26-Jun 15:53	45.2	43.0	25-Jun 15:13	57.4	22.7
Dubrovnik	25-Jun 13:57	28.6	24.1	25-Jun 14:12	32.0	14.3
Kotor	26-Jun 15:24	35.5	34.4	26-Jun 14:50	37.9	22.5
Bar	26-Jun 16:00	32.5	16.12	26-Jun 13:35	29.5	22.8
Vela Luka	*25-Jun 06:00*	*~300.0*		*25-Jun 15:06*	*108.7*	
Rijeka Dubrov.	*25-Jun 11:30*	*~250.0*		*25-Jun 14:12*	*75.1*	
Stari Grad	*25-Jun 13:00*	*~100.0*		*26-Jun 15:15*	*114.5*	
Vrboska	*25-Jun 15:00*	*~150.0*		*26-Jun 16:11*	*104.4*	
Viganj	*26-Jun 12:00*	*~80.0*		*25-Jun 15:10*	*71.2*	
Ston	*26-Jun 12:00*	*~100.0*		*25-Jun 14:22*	*60.0*	

Modeled Meteotsunami Wave



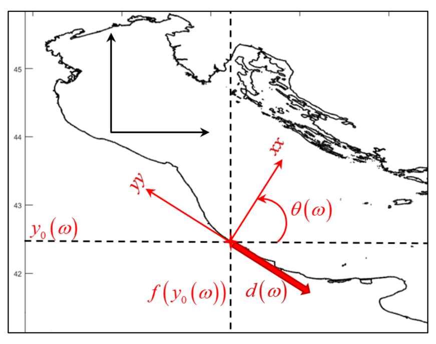
Deterministic Model Performances



Stochastic Approach: Pseudo Spectral Approximation Method

Real Meteotsunamis In Adriatic: **rare events** with **scarce observations** → **no statistics and/or coastal risk**

Idealized meteotsunamis: - **idealized pressure wave** with **7 stochastic parameters** as only forcing of ADCIRC 2D
- **mannings**' coefficient as the **8th stochastic parameter**
- **quantification of risk** → **non-intrusive Pseudo Spectral Approximation** (PSA)



$$P_{wave}(xx,yy,t,\omega)=P_A(\omega)e^{-5\frac{yy^2}{d(\omega)^2}}e^{-5\frac{(\chi(t,xx)-N(\omega)+1)\phi(t,xx)}{N(\omega)}}\sin\left(\frac{2\pi}{T(\omega)}\phi(t,xx)\right)$$

$\theta:\begin{cases}\Omega\to\mathbb{R}\\ \omega\to\theta(\omega)\end{cases}$, $\theta(\omega)\sim\mathcal{U}\left(\left[-\frac{\pi}{3},\frac{\pi}{2}\right]\right)$, wave direction

$P_A:\begin{cases}\Omega\to\mathbb{R}\\ \omega\to P_A(\omega)\end{cases}$, $P_A(\omega)\sim\mathcal{U}([50\text{Pa},400\text{Pa}])$, wave amplitude

$c:\begin{cases}\Omega\to\mathbb{R}\\ \omega\to c(\omega)\end{cases}$, $c(\omega)\sim\mathcal{U}([15\text{m s}^{-1},40\text{m s}^{-1}])$, wave velocity

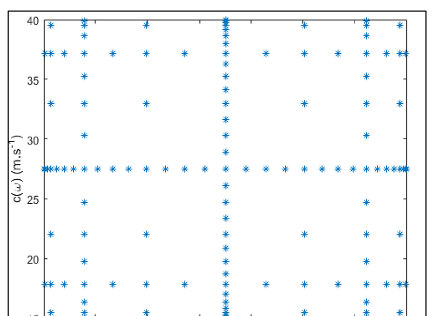
$y_0:\begin{cases}\Omega\to\mathbb{R}\\ \omega\to y_0(\omega)\end{cases}$, $y_0(\omega)\sim\mathcal{U}([41.25°,43.65°])$, start latitude

$d:\begin{cases}\Omega\to\mathbb{R}\\ \omega\to d(\omega)\end{cases}$, $d(\omega)\sim\mathcal{U}([30km,150km])$, wave width

$T:\begin{cases}\Omega\to\mathbb{R}\\ \omega\to T(\omega)\end{cases}$, $T(\omega)\sim\mathcal{U}([300\text{s},1800\text{s}])$, wave period

$N:\begin{cases}\Omega\to\mathbb{R}\\ \omega\to N(\omega)\end{cases}$, $N(\omega)\sim\mathcal{U}([2,144])$, attenuation

$n:\begin{cases}\Omega\to\mathbb{R}\\ \omega\to n(\omega)\end{cases}$, $n(\omega)\sim\mathcal{U}([0.01,0.04])$, mannings



Pseudo Spectral Approximation of order p using the **Smolyak** method:

$$\xi_{PCE}^{p,r}(x',y',t',\omega)=\sum_{\max(0,p-r+1)\le|\alpha_i|\le p}(-1)^{p-|\alpha_i|}\binom{r-1}{p-|\alpha_i|}\left(S_{\alpha_{1,i}}^{(1)}\otimes S_{\alpha_{2,i}}^{(2)}\otimes\cdots\otimes S_{\alpha_{r,i}}^{(r)}\right)$$

$r=8$ independent random input variables R_i, $i\in[\![1,r]\!]$ $R_i=\left(\frac{a_i+b_i}{2}\right)+\left(\frac{b_i-a_i}{2}\right)Z_i$, $R_i\sim\mathcal{U}([a_i,b_i])$ with $Z_i:\begin{cases}\Omega\to\mathbb{R}\\ \omega\to Z_i(\omega)\end{cases}$, $Z_i\sim\mathcal{U}(-1,1)$, $\alpha_i=[\alpha_{1,i},\alpha_{2,i},\dots,\alpha_{r,i}]$ multi-index

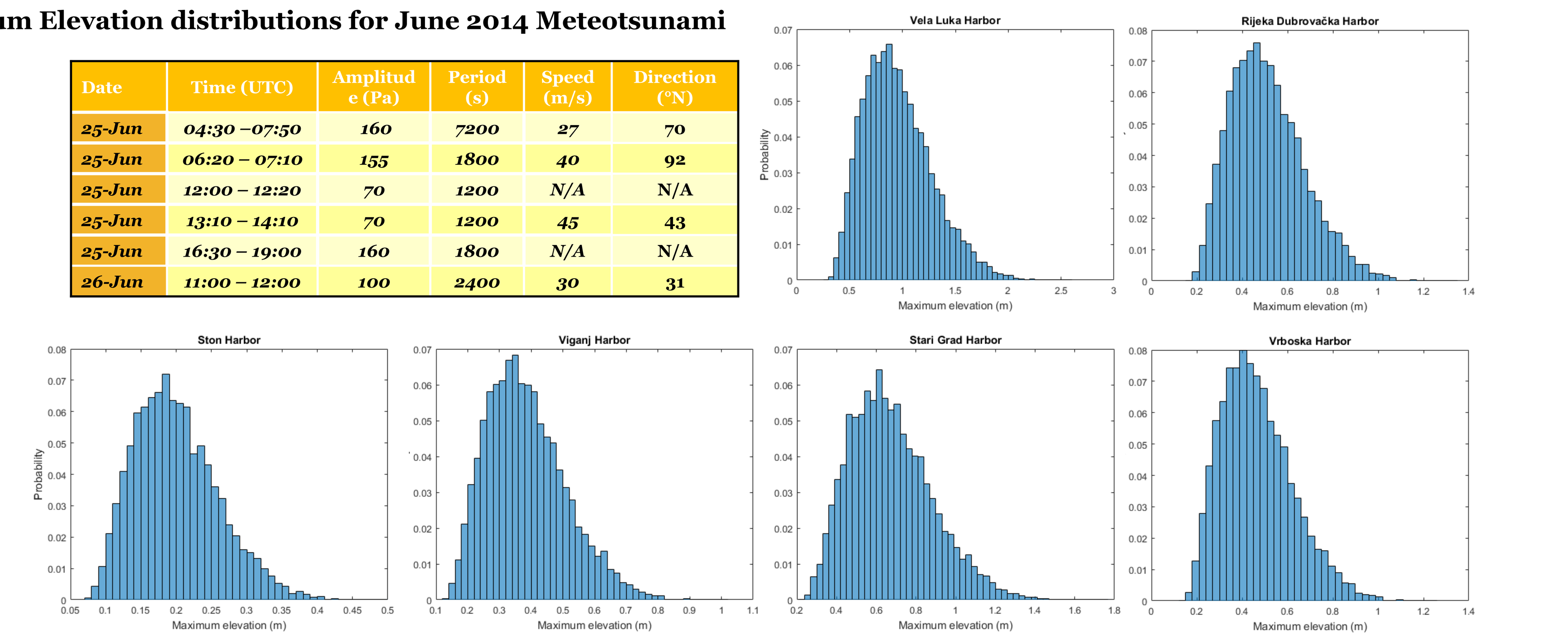
$\alpha_{j,i}$ the polynomial order associated with the Legendre polynomial $Le_{\alpha_{j,i}}$ of $R_j(\omega)$ $S_{\alpha_{j,i}}^{(j)}(g)=\sum_{\alpha=0}^{\alpha_{j,i}}\frac{Q_\alpha^{(j)}(g.Le_\alpha)}{\|Le_\alpha\|^2}Le_\alpha(R_j(\omega))$ $Q_\alpha^{(j)}(g.Le_\alpha)=\sum_{k=1}^{l}g(R_j^{(k)})Le_\alpha(R_j^{(k)})W_j^{(k)}$ is the univariate quadrature rule,

For PSA of order **p = 4** with **Gauss-Patterson sparse grids**: **6401 ADCIRC simulations**

Maximum Elevation distributions for June 2014 Meteotsunami

Preliminary Results

Date	Time (UTC)	Amplitude (Pa)	Period (s)	Speed (m/s)	Direction (°N)
25-Jun	*04:30 –07:50*	*160*	*7200*	*27*	*70*
25-Jun	*06:20 – 07:10*	*155*	*1800*	*40*	*92*
25-Jun	*12:00 – 12:20*	*70*	*1200*	*N/A*	*N/A*
25-Jun	*13:10 – 14:10*	*70*	*1200*	*45*	*43*
25-Jun	*16:30 – 19:00*	*160*	*1800*	*N/A*	*N/A*
26-Jun	*11:00 – 12:00*	*100*	*2400*	*30*	*31*



4. Conclusions

This study is a **first step towards a robust modelling** system capable of both hindcasting and forecasting meteotsunamis. It shows that the models are capable of reproducing the main physics of the meteotsunami events.

The use of the PSA method allow for assessing meteotsunami risks. However, following our early results, the method seems to underestimate the risk and there is still room for improvements …
Moreover a **multi model** approach should be used and it is planned to use one more high resolution model in addition to ADDCIRC: the **GeoClaw** model using **Adaptive Mesh Refinement**.