SPECIAL PROJECT PROGRESS REPORT

Reporting year	2021
Project Title:	Using stochastic surrogate methods for advancing towards reliable meteotsunami early warning systems
Computer Project Account:	SPCRVILI
Principal Investigator(s):	Ivica Vilibić
Affiliation:	Ruđer Bošković Institute (RBI)
Name of ECMWF scientist(s) collaborating to the project (if applicable)	Clea Denamiel (Ruđer Bošković Institute, RBI), Iva Tojčić, Petra Pranić, Petra Zemunik (Institute of Oceanography and Fisheries, IOF)
Start date of the project:	01/01/2021
Expected end date:	31/12/2023

Computer resources allocated/used for the current year and the previous one
(if applicable)

		Previous year		Current year	
		Allocated	Used	Allocated	Used
High Performance Computing Facility	(units)			20,000,000	
Data storage capacity	(Gbytes)			30,000	

Summary of project objectives (10 lines max)

Due to impossibility to properly reproduce processes at the mesoscale (~1 km), early warning systems for meteotsunamis – atmospherically-induced long ocean waves in the tsunami frequency band – are still far from providing a reliable hazard forecasts. This is particularly relevant when the realisation is coming from deterministic atmospheric and ocean models. The aim of this special project is to improve the reliability of the meteotsunami early warning systems, through improving of stochastic surrogate model by extending the pseudo-spectral approximation methodology, and by extensive testing of the model of the documented meteotsunami events. With the latter, more robust results will enlighten if the surrogate methodology may be used for better prediction of meteotsunamis.

Summary of problems encountered (10 lines max)

No major problem was encountered in terms of usage of the supercomputing facilities.

Summary of plans for the continuation of the project (10 lines max)

The project will continue in several ways: (1) by testing the methodology on higher level of the PSA method (delayed Gauss–Patterson levels 7, 8, 9, 10) and to see if any improvement in reproduction of meteotsunami stochastic forecast is reached, (2) by quantifying the reliability of the improved methodology in real meteotsunami cases, in particular of these covered nicely with the atmospheric and ocean measurements, and (3) by applying Optimal Experimental Design methodology to synthetic meteotsunami early warning systems, to find the monitoring setup that best reduce the forecast uncertainty.

List of publications/reports from the project with complete references

- Denamiel, C., Xun, H., Vilibić, I., 2021. Conceptual design of extreme sea-level early warning systems based on uncertainty quantification and engineering optimization methods. Frontiers in Marine Science, 8, 650279. https://doi.org/10.3389/fmars.2021.650279
- Tojčić, I., Denamiel, C., Vilibić, I., 2021. Performance of the Adriatic early warning system during the multi-meteotsunami event of 11–19 May 2020: an assessment using energy banners, Nat. Hazards Earth Syst. Sci. Discuss. [preprint], https://doi.org/10.5194/nhess-2020-409, in review.

Summary of results

1. Defining the conceptual design of a coastal hazard early warning systems

In this module of the project, the development of the conceptual design of stochastic surrogate early warning systems for coastal sea-level hazards has been carried out. This also included the hazard of meteorological tsunamis, for which this work fall within the scope of this ECMWF Special Project. We postulated that that fast and reliable stochastic extreme sea-level hazard assessments, using uncertainty quantification (UQ, Najm, 2009) and optimization engineering methods (Marler and Arora, 2004), can be implemented within real-time early warning systems in place of expensive state-of-the-art physical ocean model forecasts (Denamiel et al., 2021). This postulate relies on the innovative concept illustrated in Figure 1. The framework integrates advanced stochastic methods such as surrogate models based on forward UQ, Bayesian inference and optimal experimental design within an efficient operational extreme sea-level forecast system built around four main hypotheses:

Hypothesis 1: Uncertainty of extreme sea-level forecasts can be captured with stochastic forcing

Hypothesis 2: Surrogate models can shift computational needs from "online" to "offline" and achieve fast and accurate predictions

Hypothesis 3: Observational data and/or operational atmospheric forecasts can be assimilated to reduce uncertainty via Bayesian Inference at high speeds and statistical accuracy

Hypothesis 4: Optimal Experimental Design (OED) can find the most informative data in observational networks that best reduce the forecast uncertainty

Segments of this conceptual design will be further developed, implemented and tested on a meteotsunami early warning system, also in this ECMWF Special Project.

2. Application of stochastic surrogate early warning system to a multi-meteotsunami event

To test the reliability of the meteotsunami stochastic surrogate model in operational (forecast) mode, developed by Denamiel et al. (2019), the multi-meteotsunami event lasting for 9 days in the middle Adriatic Sea has been used. Such an event is unusual for the Adriatic Sea (Vilibić and Šepić, 2009) and in general (Monserrat et al., 2006), so that posing a great opportunity to do the testing of the system. The manuscript coming from this research is currently under the review in journal Natural Hazards and Earth System Science (Tojčić et al., 2021). This event is of particular interest because meteotsunamigenic synoptic patterns over the Adriatic were present during a prolonged period of about 5 to 10 days, not previously observed for any meteotsunami (Monserrat et al., 2006; Vilibić and Šepić, 2009; Vilibić et al., 2021). During this period, intense high-frequency air pressure and sea-level oscillations were observed and recorded in the middle Adriatic with maximum sea-levels reached the 11th, 14th and 16th of May in Vela Luka, Stari Grad and Vrboska (Fig. 2).

The Croatian meteotsunami early warning system (CMeEWS) is composed of a network of air pressure and sea level observations, a high-resolution atmosphere-ocean modelling suite and a stochastic surrogate model. The CMeEWS, which is not operational due to a lack of numerical resources, was used retroactively to reproduce the multiple events observed in the eastern Adriatic between the 11th and 19th of May 2020. The performances of the CMeEWS deterministic models are then assessed with an innovative method using energy banners based on temporal and spatial spectral analysis of the high-pass filtered air pressure and sea-level fields. It was demonstrated that, even though the strongest atmospheric activity was modelled in the middle Adriatic along common air pressure disturbance pathways, the meteotsunami events were always missed by the ADCIRC ocean model at Vela Luka and Stari Grad during the 11-19 May 2020 period due to a shift in location of the modelled atmospheric disturbances. This most probably indicates that the frequency of the air pressure disturbances is not properly reproduced by the WRF 1.5-km model, posing a question of appropriateness of the state-of-the-art atmospheric models in terms of their resolution and setup (Horvath and Vilibić, 2014). Finally, in operational mode, the stochastic surrogate model would have triggered the warnings for most of the observed events, but also setting off some false alarms. Due to the uncertainties associated with operational modelling of meteotsunamigenic disturbances, the stochastic approach has thus proven to overcome the failures of the deterministic forecasts and should be further developed.

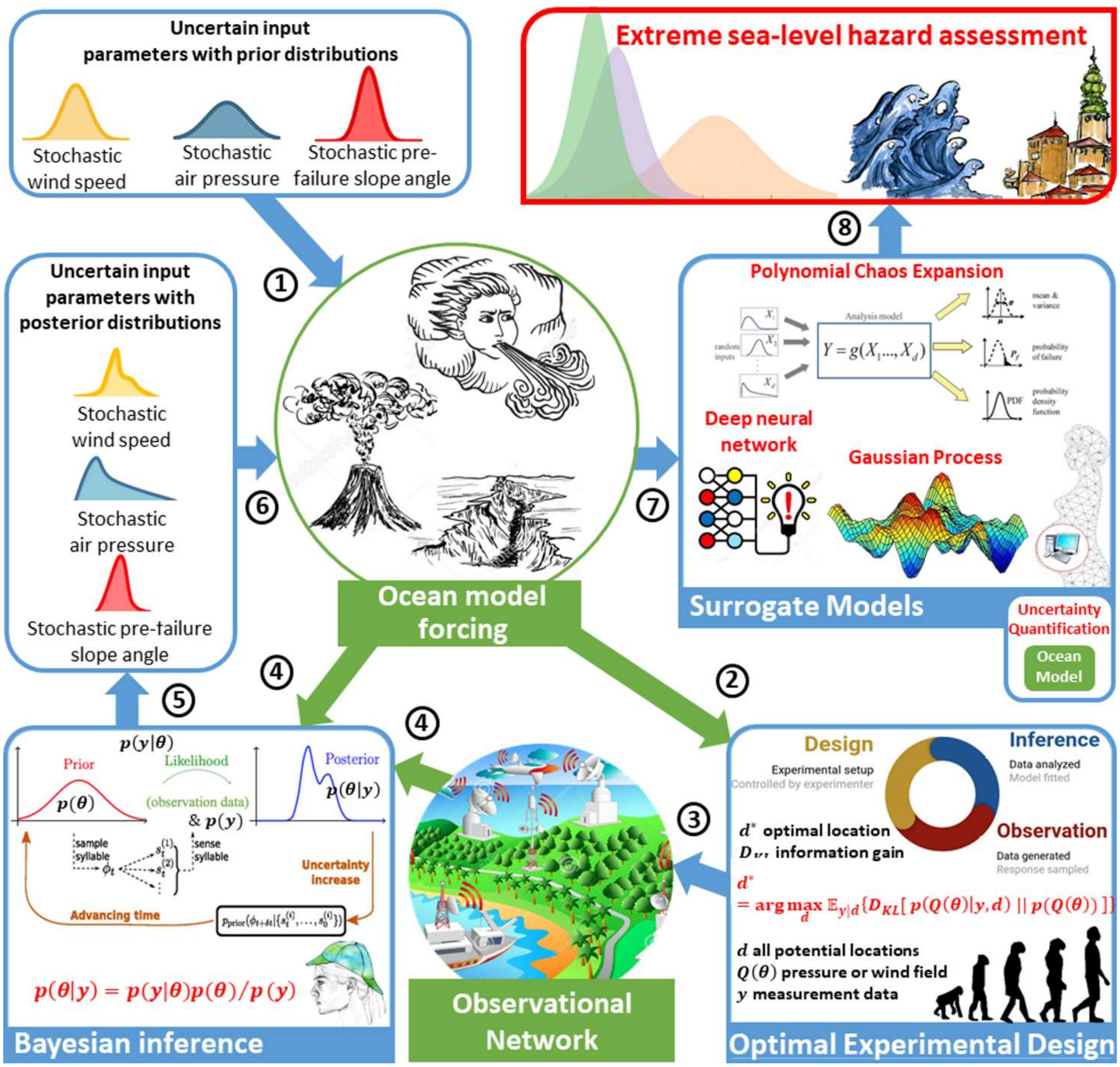

Figure 1. Extreme sea-level hazard assessments based on uncertainty quantification and optimization engineering methods (after Denamiel et al., 2021): 1) uncertain input parameters with prior distribution are used to create stochastic ocean model forcing which are both 2) and 3) used to optimized the observational network with optimal experimental design strategies and 4) modified with the assimilation of observational data via Bayesian inference in order to 5) create the posterior distributions of the input parameters. Finally, 6) new stochastic ocean forcing based on these parameters are used to force 7) the surrogate models and produce 8) extreme sea-level hazard assessments. Drawing of the flooded city adapted from Frits Ahlefeldt: https://fritsahlefeldt.com/2019/01/24/not-ready-city-facing-flooding.

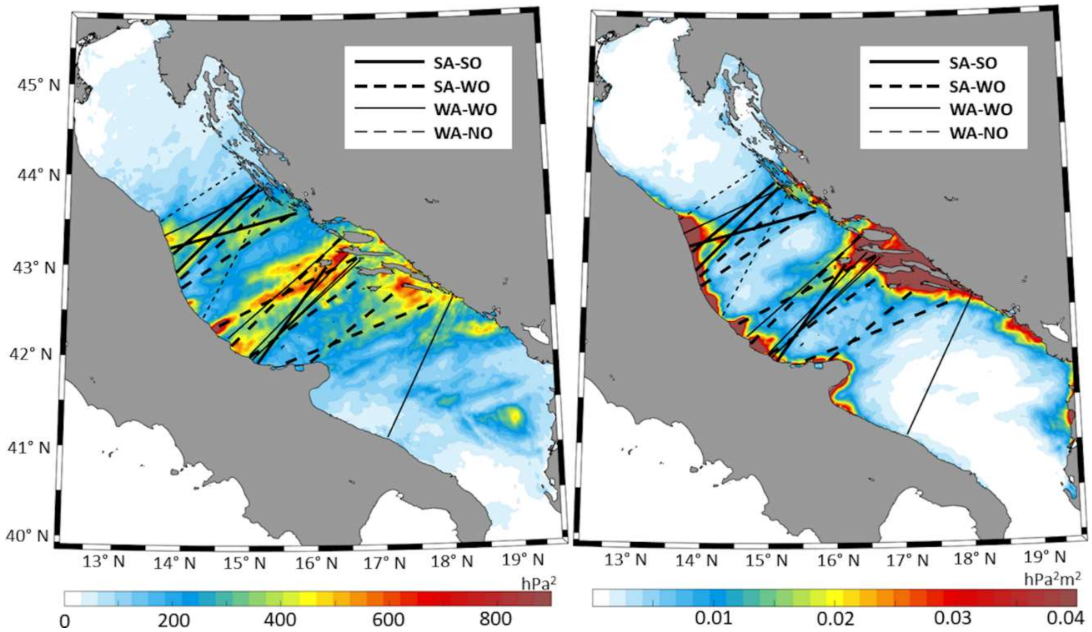

Figure 2: Averaged air pressure variances (left panel) and averaged new transect sampling criterion (right panel) estimated for the ensemble of transects extracted between the 11th and 19th of May 2020 (after Tojčić et al., 2021). The modelled disturbances (black lines) are categorized depending on the strength of the atmospheric signal (SA for strong and WA for weak) and the ocean response (SO for strong, WO for weak, NO for none).

3. Development of the Optimal Experiment Design strategy for the least uncertain meteotsunami early warning systems

Here, a new formulation and computational algorithm for performing Optimal Experimental Design (OED) has been under development in the first six months of the project. This approach differs from existing classical OED methods in that a *goal-oriented* objective are optimized. As an example, consider an OED problem where we seek to place sensors in the ocean to take atmospheric pressure measurements associated with meteotsunamis. The existing formulation would then seek to optimize the sensor locations such that the uncertainty in the model forcing parameters can be reduced to the greatest extent. This quantitative objective is the expected information gain (EIG) in the model parameters: $\mathbb{E}_{y|d}[\,D_{KL}[\,p(\theta|y,d)||\,p(\theta)]]$, where θ denotes the uncertain forcing parameters, y denotes the pressure measurement, and d is the design choice (i.e. sensor location). In other words, the change of the (updated) posterior uncertainty compared to the prior uncertainty has been maximized as a result of having the sensor's measurement at location d.

In such a new goal-oriented approach, we take the perspective that learning parameters θ is typically not the end goal, but rather we are often interested in making new predictions on a goal-quantity $z = H(\theta)$ that depends on the estimated θ. Thus, we present the goal-oriented EIG on the new predictive quantity: $\mathbb{E}_{y|d}[\,D_{KL}[\,p(z|y,d)||\,p(z)]]$. For instance, while we first use the sensor pressure measurements y to learn the forcing parameters θ via an atmospheric model, we then use these forcing parameters θ to predict the wave height z at specific harbours through an ocean model. This flow is depicted in Figure 3.

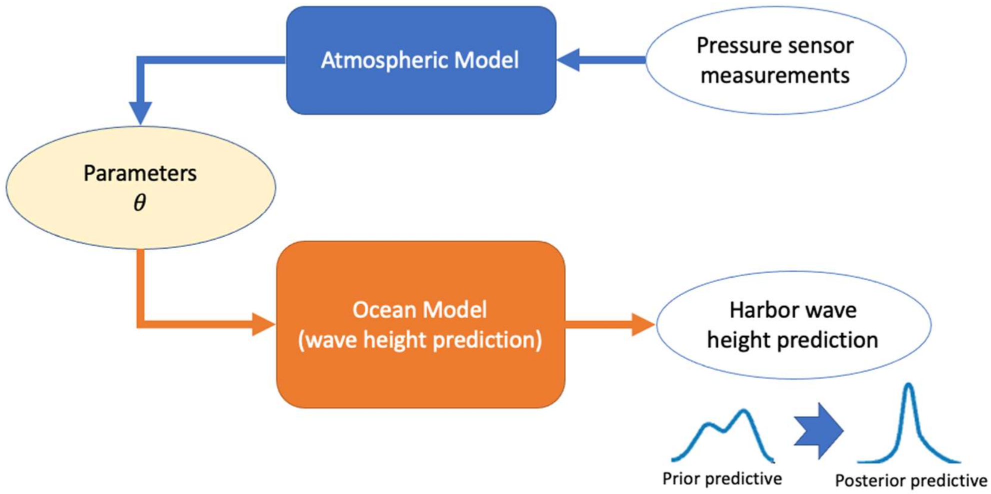

Figure 3: The flow of the OED to be applied for meteotsunamis.

Numerically solving the new goal-oriented OED is non-trivial. It requires the following steps:

1. Starting from a candidate design d. From the prior distribution of θ, sample different possible sensor measurements that we may obtain at this sensor design location.
2. For each of the possible measurement outcomes, perform Bayesian inference to obtain the posterior for θ. This requires an expensive Markov chain Monte Carlo (MCMC) sampling and using the Atmospheric Model.
3. Once MCMC is complete, run each of the posterior θ samples through the Ocean Model in order to predict what the wave height would be under that scenario.
4. This then yields the posterior predictive distribution of the wave height z. We can then compare to the prior predictive distribution for the wave height in order to estimate the EIG on this goal-quantity z.
5. Perform optimization over the design space to find the optimal d that maximizes the EIG on the goal-quantity z.

4. Conclusions

In the first six months of this ECMWF Special Project, several research activities has been initiated to properly tackle different aspects of meteotsunami warning systems, in particular of: (1) its upgraded and generalized conceptual design, (2) application of existing meteotsunami early warning system to unusual occurrence of meteotsunamis, and (3) application of Optimal Experimental Design method within the meteotsunami early warning systems, specifically for reducing uncertainty coming from observational networks. We progressed in all of these aspects, reaching well-read publication in Frontiers in Marine Sciences, that was even noticed and tweeted by the ECMWF staff. Further, a promising result in applying of the meteotsunami early warning system to the multi-meteotsunami event allowed for writing of the manuscript, that would hopefully be accepted in a high-quality peer-reviewed journal (presently under second round of reviews). Further, a completely new application to meteotsunami warning systems has been in progress, using an optimization method for meteotsunami-observing systems within the early warning systems – that might largely improve the meteotsunami science, in the case that the method is providing reasonable results. Altogether, the project is running fine, with several publications foreseen in the second year of the project.

References

Denamiel, C., Xun, H., Vilibić, I., 2021. Conceptual design of extreme sea-level early warning systems based on uncertainty quantification and engineering optimization methods. Frontiers in Marine Science, 8, 650279. https://doi.org/10.3389/fmars.2021.650279

Denamiel, C., Šepić, J., Huan, X., Bolzer, C., Vilibić, I., 2019. Stochastic surrogate model for meteotsunami early warning system in the eastern Adriatic Sea. Journal of Geophysical Research Oceans, 124, 8485-8499, https://doi.org/10.1029/2019JC015574

Horvath, K., Vilibić, I., 2014. Atmospheric mesoscale conditions during the Boothbay meteotsunami: a numerical sensitivity study using a high-resolution mesoscale model. Natural Hazards, 74, 55-74, https://doi.org/10.1007/s11069-014-1055-1

Marler, R.T., Arora, J.S., 2004. Survey of multi-objective optimization methods for engineering. Struct. Multidiscipl. Optim., 26, 369-395. https://doi.org/10.1007/s00158-003-0368-6

Monserrat, S., Vilibić, I., Rabinovich, A.B., 2006. Meteotsunamis: atmospherically induced destructive ocean waves in the tsunami frequency band. Natural Hazards and Earth System Sciences, 6, 1035-1051, https://doi.org/10.5194/nhess-6-1035-2006.

Najm, H.N., 2009. Uncertainty quantification and polynomial chaos techniques in computational fluid dynamics. Ann. Rev. Fluid Dyn. 41, 35-52. https://doi.org/10.1146/annurev.fluid.010908.165248

Tojčić, I., Denamiel, C., Vilibić, I., 2021. Performance of the Adriatic early warning system during the multi-meteotsunami event of 11–19 May 2020: an assessment using energy banners, Natural Hazards and Earth System Sciences Discussions [preprint], https://doi.org/10.5194/nhess-2020-409, in review.

Vilibić, I., Šepić, J., 2009. Destructive meteotsunamis along the eastern Adriatic coast: Overview. Physics and Chemistry of the Earth, 34, 904-917. https://doi.org/10.1016/j.pce.2009.08.004

Vilibić, I., Denamiel, C., Zemunik, P., Denamiel, C., 2021. The Mediterranean and Black Sea meteotsunamis: An overview. Natural Hazards, 106, 1223–1267, https://doi.org/10.1007/s11069-020-04306-z