SPECIAL PROJECT PROGRESS REPORT

Reporting year	2023
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, Iva Tojčić (Ruđer Bošković Institute, RBI), 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)	15,000,000	15,000,000	10,000,000	4,000,000
Data storage capacity	(Gbytes)	50,000	50,000	65,000	50,000

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 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 downscaling meteotsunamis in the present climate by using coupled (sub-)kilometre-scale atmosphere-ocean models, with the selected test events through synoptic index-based model and from meteotsunami catalogues, and (2) by quantifying planetary hazard of meteotsunamis generated by past and potential volcanic explosions coming from super-volcano sites in the world, through coupling of global atmospheric and ocean numerical models.

List of publications/reports from the project with complete references

- Denamiel, C., Vasylkevych, S., Žagar, N., Zemunik, P., Vilibić, I., 2023. Destructive potential of planetary meteotsunami waves beyond the Hunga volcano eruption (Tonga). Bulletin of the American Meteorological Society, 104, E178–E191. https://doi.org/10.1175/BAMS-D-22-0164.1
- Denamiel, C., Belušić, D., Zemunik, P., Vilibić, I., 2023. Climate projections of meteotsunami hazards. Frontiers in Marine Science, under revision.

Summary of results

The research done in the last year was continuation of activities carried out in the previous year: (1) building the concept of synoptic-index based downscaling of meteotsunami events, which will serve as an input for assessment of meteotsunami hazard, and (2) widening the concept of explosive volcano eruption anywhere around the globe, based on of the Hunga volcano in January 2022 and the generated planetary atmospheric waves (Lamb waves) that caused planetary meteotsunami waves. The latter has been reported in the previous report, so it will not be reported here.

Building the synoptic index-based model for meteotsunami hazard

Global climate models, indispensable for projecting the human-driven climate change, have been improving for decades and are nowadays capable of reproducing multiple processes (e.g., aerosols, sea-ice, carbon cycle) at up to 25 km horizontal resolution. Meteotsunami events – tsunami waves generated by mesoscale atmospheric processes – are properly captured only by sub-kilometre-scale downscaling of these models. However, the computational cost of long-term high-resolution climate simulations providing accurate meteotsunami hazard assessments would be prohibitive. To overcome this deficiency, a new methodology is introduced, allowing to project sub-kilometre-scale meteotsunami hazards and their climate uncertainties at any location in the world. Practically, the methodology uses (1) synoptic indices to preselect a substantial number of short-term meteotsunami episodes and (2) a suite of atmospheric and oceanic models to downscale them from an ensemble of global models to the sub-kilometre-scale. Such approach, using hundreds of events to build robust statistics, could allow for an objective assessment of the meteotsunami hazards at the climate scale which, on top of sea level rise and storm surge hazards, is crucial for building adaptation plans to protect coastal communities worldwide.

In the last decade, numerical modelling and forecast of meteotsunami events – tsunami waves generated by travelling atmospheric disturbances (Monserrat et al., 2006) – has been a pressing issue for the development of meteotsunami early warning systems (Vilibić et al., 2016). However, many challenges have already been overcome and more and more early warning systems and high-resolution modelling suites are nowadays capable to capture meteotsunami events (e.g., Renault et al., 2011; Anderson and Mann, 2021; Tojčić et al., 2021; Sun and Niu, 2021; Angove et al., 2021; Rahimian et al., 2022; Kim et al., 2022).

Historically, three complementary avenues have been explored: (1) synoptic indices, (2) high resolution numerical models and (3) ensemble or stochastic approaches. Synoptic indices – connecting atmospheric patterns with meteotsunami events – have only been successfully used in the Balearic Islands, Spain (Ramis and Jansà, 1983). However, they have recently been derived worldwide and strong connections between meteotsunami events and synoptic patterns have been found along most of the world's coastlines, but particularly at mid-latitudes (Šepić et al., 2016; Zemunik et al., 2022). The advantage of the approach is that no additional numerical cost is required, as synoptic indices – identifying meteotsunami events up to a week in advance – can be derived and used with relatively coarse weather models (30-80 km in resolution). The major drawback is the impossibility to quantify the intensity of the events due to the important contribution of mesoscale processes not captured by the synoptic indices. Consequently, the implementation of operational coupled atmosphere-ocean modelling suites at the sub-kilometre scale is an unavoidable necessity in early warning systems. To this date, they have only been implemented in the Balearic Islands (Renault et al., 2011) and the Adriatic Sea (Denamiel et al., 2019a, 2019b). In both systems the meteotsunamigenic disturbances triggering the event mode of the early warning systems are always detected and the meteotsunami hazards are quantified for the known hot spot locations. However, even for a 3-day forecast, running sub-kilometre scale models has been proven to have a prohibitive numerical cost and, for the Adriatic Sea, the operational forecasting service was discontinued. Finally, deterministic forecasts of meteotsunami events often fail and meteotsunami hazards can only be properly quantified via ensemble or stochastic approaches. However, ensembles of kilometre-scale (or km-scale) atmospheric models have an enormous computational cost and were only tested as an academic exercise in the Balearic Islands (Mourre et al., 2021). Stochastic methods (Geist et al., 2014; Vich and Romero, 2021) and surrogate models or ocean emulators (Denamiel et al., 2019b, 2020a, 2021) for meteotsunami hazards are thus promising avenues. They have been implemented in the Balearic Islands and the Adriatic Sea, where they can run operationally at nearly no numerical cost despite being numerically expensive to design (Tojčić et al., 2021).

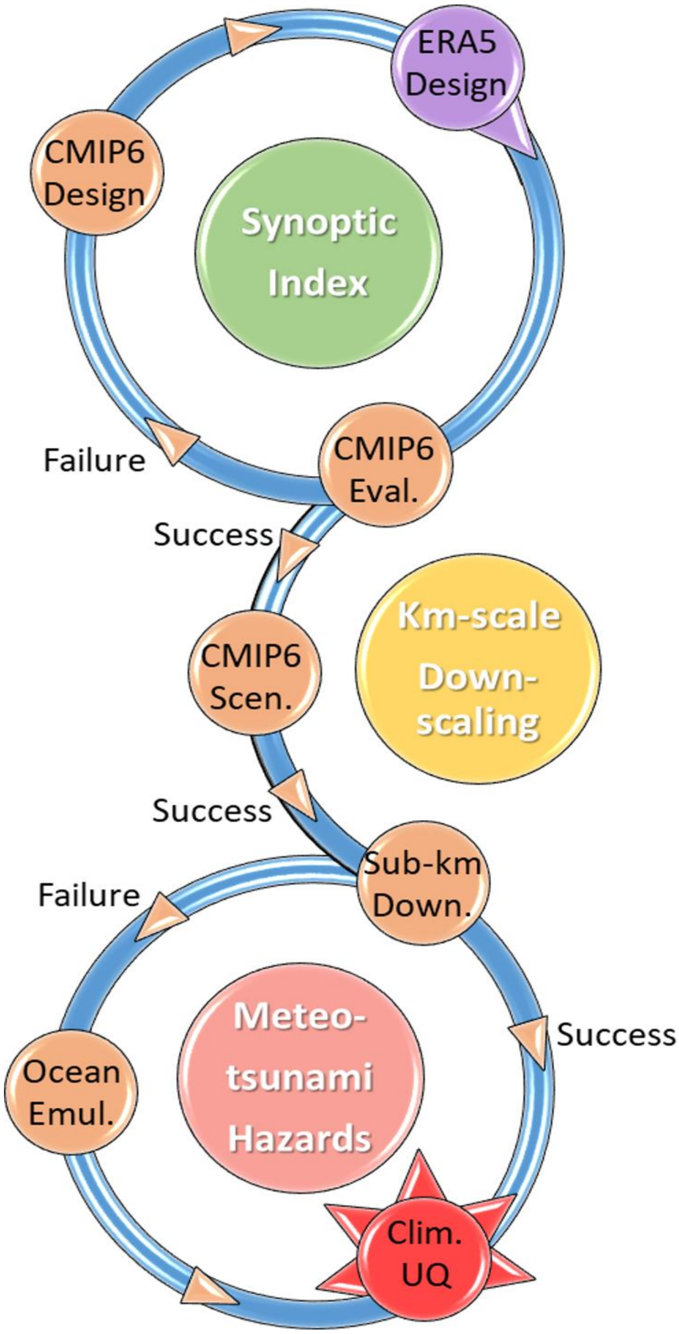

Figure 1. Workflow of the methodology for projecting meteotsunami hazards using synoptic indices designed with global reanalysis products (ERA5 Design) and GCM historical simulations (CMIP6 Design) to derive targeted meteotsunami hazards including the climate uncertainty (Clim. UQ) by downscaling (Km-scale Downscaling and Sub-km Down.) historical (CMIP6 Eval.) and future (CMIP6 Scen.) GCM simulations and using ocean emulators (Ocean Emul.).

Following these major advances, climate projections of meteotsunami hazards are the next big challenge faced by the meteotsunami community. Indeed, as these extreme events are driven by atmospheric conditions highly influenced by the on-going global warming, understanding the impact of climate change on the meteotsunami recurrence and intensity could be critical for the adaption plans of the coastal communities worldwide. However, till now, little is known about this issue as only two studies have tried to quantify the impact of global warming on meteotsunami hazards. One used the synoptic index-based approach in the Balearic Islands (Vilibić et al., 2018) and found that meteotsunami occurrences could increase by one third under extreme warming conditions (Representative Concentration Pathway RCP 8.5 scenario). The other used the pseudo-global warming (PGW) downscaling approach (Schär et al., 1996; Denamiel et al., 2020b) for half a dozen meteotsunami events in the Adriatic Sea (Denamiel et al., 2022) and found a strong impact of climate warming on the spatial variability of the meteotsunami intensity under RCP 8.5 scenario. However, both studies were carried out with a single Regional Climate Model (RCM) and for a single climate scenario, and thus do not account for the climate uncertainty.

In this research the methodology that could be used to lower the computational costs of sub-kilometre-scale meteotsunami climate modelling has been developed, while keeping a fair description of the climate projection uncertainties. The methodology has been based of four hypotheses:

Hypothesis 1: Conditions for local meteotsunami events can be seen and automatically extracted at the synoptic level.

Hypothesis 2: Uncertainty in climate projections can be captured by sub-sampling meteotsunami events only.

Hypothesis 3: Short-term simulations are suitable for the kilometre-scale reproduction of meteotsunami events.

Hypothesis 4: Targeted climate hazard assessments are crucial for extreme event adaptation.

Practical implementation of the methodology follows the seven steps of the workflow presented in Figure 1.

Conclusions

In the last twelve months of this ECMWF Special Project, several research activities have been carried out to properly tackle different aspects of meteotsunami hazard. Investigations of future climate of meteotsunamis, by developing a model of the synoptic index-based selection and downscaling of events, have been under way. The model will be implemented hopefully soon, once the Hypothesis 1 will be proven, which is a prerequisite for implementing climate downscaling and estimation of meteotsunami hazards in the present and future climates. Also, the strategy for getting coastal hazards coming from atmospheric waved generated by explosive volcanic eruption is developed and will be implemented in the next years.

References

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