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Discussions

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# Response to the reviewers' comments on the manuscript "Performance of the Adriatic early warning system during the multi-meteotsunami event of 11-19 May 2020: an assessment using energy banners" by Tojčić et al., submitted to NHESS (nhess-2020)

Iva Tojčić et al.

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Author comment on "Performance of the Adriatic early warning system during the multi-meteotsunami event of 11–19 May 2020: an assessment using energy banners" by Iva Tojčić et al., Nat. Hazards Earth Syst. Sci. Discuss., https://doi.org/10.5194/nhess-2020-409-AC1, 2021

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The authors would like to thank anonymous reviewer for his/hers detailed comments which will help to largely improve the next version of the article.

**Anonymous Reviewer #1 (RC1)**

*"Performance of the Adriatic early warning system during the multi-meteotsunami event of 11-19 May 2020: an assessment using energy banners" is an interesting manuscript concerned with using numerical methods to forecast meteotsunami in coastal areas. The article contains a detailed description of the forecasting system performance during the multi-meteotsunami event that hit the eastern Adriatic coast in 2020. The objective of numerical experimentation is clearly stated. I must say, however, I had some difficulties in reading the manuscript and follow the author's approach. As it is now, I cannot evaluate the capacity of the modelling system in forecasting meteotsunami events.*

**Response:** Thank you for your comments. A "Methods" section will be introduced in the next version of the article. We hope that it will help to clarify and simplify the article and hence to make it easier for the readers to follow the study.

*An unclear point of this study is the definition of the disturbance trajectories (transects) and associated energy banners. Part of section 5 should be moved before (or at the beginning) of section 4 in order to understand the presented results. On this topic, the authors should clear explain:*

- *how the transects are selected;*
- *the number of transect per event;*
- *how to compare model results with observation at different locations (figures 3 to 5). As they are now, these figures are not useful for understanding the model*

performance;

- *what's the temporal rate of change for identifying events (on which time interval);*
- *why the transect sampling criteria, which accounts for the open-ocean resonance, does not provide useful indications for selecting the transects.*

**Response:** We agree with the reviewer that the methodologies used in the article were not clearly described. We will add the following "Methods" section in order to address the first four bullet points raised above:

"In order to evaluate the capacity of the CMeEWS to provide meaningful meteotsunami hazard assessments, the AdriSC modelling suite is run in operational (hindcast) mode after the 11-19 May 2020 multi-meteotsunami event took place. This means that the 10-day forecasts derived with the ECMWF HRES and MEDSEA/MSF models on the 8th, 9th, 10th, …, 16th of May 2020 are used to hindcast the meteotsunamigenic conditions of the 11th, 12th, 13th, …, 19th of May 2020. However, as no meteotsunamigenic disturbances were recorded during the 12th and 13th May (Fig. 1), these two days are not simulated in order to spare some numerical resources. The model is set-up to run for short periods of three days in the basic module and one and a half day in the extreme event module, with only the last 24-h hourly results – extracted from the WRF 1.5-km model in the atmosphere and the ADCIRC unstructured model in the ocean – used in the following analyses. Within the CMeEWS, the meteotsunamigenic disturbances reproduced with the AdriSC WRF 1.5-km model are automatically detected if the maximum temporal rate of change (i.e. pressure difference calculated over a 4□min interval) of the high-pass filtered air pressure derived at each WRF 1.5□km grid sea point is above 20 Pa/min over at least 5% of the sea domain. Such a condition has been proven to be efficient for the detection of meteotsunamigenic disturbances (Vilibić et al., 2016; Denamiel et al., 2019b). The event mode of the system (i.e. meteotsunamis may occur) is thus triggered without human interventions for the studied 11-19 May 2020 period.

Hereafter, air pressure and sea-level data both derived with the AdriSC modelling suite and collected from the stations listed in Table 1, are filtered using a 2-h Kaiser–Bessel filter to extract high frequency pressure and sea-level oscillations characteristic for meteotsunamis. At a very basic level, a direct comparison of modelled (blue lines, Fig. 1) and measured (red lines, Fig. 1) high-pass filtered air pressure and sea-level time series is used in Section 4 to assess the capacity of the AdriSC deterministic model to reproduce the meteotsunami events at the locations of interest during the middle Adriatic multi-meteotsunami event of 11-19 May 2020.

Since the failure of deterministic models to reproduce the small scale atmospheric disturbances at the right locations is a known problem, the verification of the AdriSC WRF 1.5-km results presented in Section 5 tracks the locations where the highest daily spectral energies occur in both the model and the observations. In other words, the performance of the AdriSC WRF 1.5-km model is derived with Fast Fourier Transforms (FFT) analyses (Cooley and Tukey, 1965) of the high-pass filtered air pressure observed and modelled results calculated every 30 min with a 3-h window at selected locations for each day of the reproduced multi-meteotsunami event. First, as the meteotsunamigenic disturbances are known to propagate from the Western to the Eastern Adriatic (Vilibić and Šepić, 2009; Denamiel et al., 2020), 5 transects are selected to track the modelled atmospheric disturbances: 2 transects along the Italian coast in the Western Adriatic (T4 and T5), one in the Middle Adriatic (T3) and two transects along the Croatian coast in the Eastern Adriatic (T1 and T2). Then, for each day of the multi-meteotsunami event, the AdriSC WRF 1.5-km results are extracted at the actual microbarograph locations and in additional model grid points (black dots, Fig.1) selected where the highest daily spectral energies are reproduced by the model along the Western (selected points W1 to W7), Middle (selected points M1 and M2), and Eastern Adriatic (selected points E1 to E6) transects. Finally, for each day with a meteotsunami event, the time evolutions of the spectra derived from the observations (at the microbarograph location where the meteotsunami was best observed – i.e. highest spectral energy along the Western Adriatic transect for Ancona, Ortona and Vieste microbarographs, along the Middle Adriatic transect for Vis and Svetac microbarographs and along the Eastern Adriatic transect for Vrboska, Stari Grad and Vela Luka microbarographs) are compared with the time evolutions of the spectra derived from the WRF 1.5-km results at the point where the highest energy was reproduced (including microbarograph locations). At the end, for the entire duration of the multi-meteotsunami event, composites of frequency-time spectrograms of high-pass filtered air pressure observed and modelled data for the Western, Middle and Eastern Adriatic regions are created (Figs. 3-5).

The analyses performed in Section 6 are done in two steps and aim to better track the propagation of the modelled meteotsunamigenic disturbances across the Adriatic Sea, in order to improve the extraction of the atmospheric parameters needed to run the stochastic surrogate model. In the first step, two different transect sampling criteria are used to select the transects along which the atmospheric disturbances, and hence the meteotsunami waves, propagate in the model: one based solely on the atmospheric results (already used operationally) and a new one also taking into account the ocean results (tested in this study). For the operational sampling criterion, the time variances of the WRF 1.5-km high-pass filtered air pressure results are calculated on a 3-hour interval (i.e. 8 time-windows per day) over the entire model domain. For each event occurring during the 11-19 May 2020 period, the transects presented in this study are selected across the Adriatic Sea following the paths of highest atmospheric variances for the most energetic time-windows. Since the number of time-windows and paths with high air pressure variances varies between the events, the number of transects for each day varies too. For the new sampling criterion, the variances of the high-pass filtered air pressure and sea-level model results estimated on a 3-hour interval are multiplied. This criterion thus tends to zero when the atmospheric forcing does not trigger any ocean response, i.e. when no resonant transfer of energy from the atmosphere to the sea is occurring. It should be noted that such a criterion could not be directly derived from the sea-level variances which provide a noisy and mostly untraceable signal due to the numerous interactions of the ocean waves with the bathymetry including, for example, the reflection and refraction around the islands. Hereafter the new transect sampling criterion is compared with the operational one in order to determine whether or not it would have improved the transect selection. In the second step, meteotsunami energy banners defined as the spectrograms of the modelled high-pass filtered air pressure and sea-level results are spatially calculated with FFT along the selected transects for the 3-h time-window corresponding to the operational transect sampling criterion. As speed remains a difficult parameter to extract from the observed and modelled meteotsunamigenic disturbances, speeds of the tracked atmospheric disturbances along the transects are also visually determined by analysing the propagation along the transects of the strongest WRF 1.5-km high-pass filtered air pressure peaks. The locations where the Proudman resonance is likely to occur along the transects are then derived by calculating where the Froude number ($Fr=U/C$) ranges from 0.9 and 1.1 (i.e. where the speed of the atmospheric disturbances $U$ are matching the speed of the long ocean waves $C=\sqrt{gH}$, with $g$ the gravitational acceleration and $H$ the local depth). The analyses from Section 6 are presented with one transect (plotted from West to East following the propagation of the meteotsunami events) per event in the article (Transect 1, Figs. 6-10) selected during the peak of the modelled daily event and as supplementary material for the other transects (Figs. S2-S15) in order to keep a reasonable article length.

Finally, for each day of the multi-meteotsunami event, the input parameters of the stochastic surrogate model are then manually extracted from the AdriSC WRF 1.5-km modelled atmospheric disturbances along the transects selected in Section 6. The probabilities of the maximum elevation surpassing the flooding thresholds in the Vela Luka, Stari Grad and Vrboska harbours, where flooding occur during the 11-19 May 2020 period, are then determined and the meteotsunami hazards assessed for each separate event."

Regarding the fifth bullet point, we will add the following clarification at the end of Section 8 (Summary and conclusions):

"Finally, the introduced transect sampling criteria does not seem to overall facilitate the decision-making process in terms of the transect selection, since all the transects selected by this criterion would have also been selected following highest values of air pressure variances only. Even though for some events (e.g. Figs. 8, 9, 10) the new criterion highlights the strength of the air-sea interactions, these interactions are located along the same transects as captured by the highest values of the air pressure variance. As efficiency is important in early warning system, it can thus be concluded that the use of the ocean model results to better select the transect with maximum meteotsunami generation is not necessary in operational mode, since it would be more time consuming with no significant value added to the process of the transects selection."

*Moreover, some aspects mainly related to the Meteotsunami Early Warning System need to be improved. The authors should provide more details about:*

- *the numerical models' implementation, e.g. model domains, grid resolution, boundary and forcing conditions;*
- *the observational systems, e.g. type of instruments, acquisition frequencies, filtering of the wind-wave effects on the tide gauge data;*
- *high-pass filtering procedure of observation and model results.*

**Response:** Accepted.

First bullet point will be addressed with the following paragraph:

"The basic module uses a modified version of the Coupled Ocean-Atmosphere-Wave-Sediment-Transport (COAWST) modelling system developed by Warner et al. (2010), built around the Model Coupling Toolkit (MCT) which exchanges data fields and dynamically couples the Weather Research and Forecasting (WRF) atmospheric model, the Regional Ocean Modeling System (ROMS), and the Simulating WAves Nearshore (SWAN) model. The basic module is set-up with (1) two different nested grids of 15-km and 3-km resolution used in the WRF model and covering respectively the central Mediterranean area and the Adriatic-Ionian region and (2) two different nested grids of 3-km and 1-km resolution used for both ROMS and SWAN models and covering respectively the Adriatic-Ionian region (similarly to the WRF 3-km grid) and the Adriatic Sea only.

The dedicated meteotsunami module couples offline the Weather Research and Forecasting (WRF) model (Skamarock et al., 2005) with the 2DDI (i.e. two-dimensional depth-integrated) unstructured ADvanced CIRCulation (ADCIRC) model (Luettich et al., 1991), using a mesh of up to 10-m in resolution in the areas sensitive to meteotsunami hazard. In more details, (1) the hourly results from the WRF 3-km grid obtained with the basic module are first downscaled to a WRF 1.5-km grid covering the Adriatic Sea and (2) the hourly sea surface elevation from the ROMS 1-km grid, the 10-min spectral wave results from the SWAN 1-km grid and the 1-min results from the WRF 1.5-km grid are then used to force the unstructured mesh of the ADCIRC-SWAN model. In this deterministic configuration, the ADCIRC model is forced every minute by the WRF 1.5-km wind and pressure fields, and every hour by the basic module sea-level fields (including tides) at the open sea boundary (Otranto Strait)."

Second bullet point will be addressed with the following paragraph:

"The observational network (called MESSI, www.izor.hr/messi) consists of nine microbarographs, of which eight are used in this study, measuring air pressure by the Väisälä PTB330 sensor with an accuracy of ±0.01 hPa, and three tide gauges, of which two are used in this study, measuring sea-level by the OTT RLS radar level sensor with an accuracy of ±1 mm. All instruments are setup with a 1☐min sampling rate and listed in Table 1."

The last bullet point will already be addressed in the "Methods" section defined above.

*line 75: "(2) measurements from the MESSI (www.izor.hr/messi) observational network" does not provide useful information. I suggest replacing with: "(2) high-frequency air pressure and sea level measurements along …"*

**Response:** Accepted. We will replace it with:

"(2) high-frequency air pressure and sea-level measurements along the Adriatic coast…"

*line 84: … with the 2D unstructured ADvanced CIRCulation (ADCIRC) model …*

**Response:** Accepted. We will replace with:

"with the 2DDI (i.e. two dimensional depth-integrated) unstructured ADvanced CIRCulation (ADCIRC) model"

*line 87: … sea-level fields (including tides) at the open sea boundary (Otranto Strait).*

**Response:** Accepted. We will replace the existing line with:

"…sea-level fields (including tides) at the open sea boundary (Otranto Strait)."

*I strongly suggest splitting Figure 1 in two: the first containing only the map and putting all time series on a separate figure 2. Depth should be positive.*

**Response:** In order to limit the number of figures in the article (which is already large), we will keep the figure as one but put all the time series in two columns below the map, to fit with the journal format. Also, we will change the depth sign into positive.

*Remove lines 98-101.*

**Response:** Accepted. Those lines will be removed.

*line 110: The observational network (called MESSI, www.izor.hr/messi), …*

**Response:** Accepted. We will replace the existing line with:

"The observational network (called MESSI, www.izor.hr/messi)..."

*line 116: … at the tops of the bays that are normally most affected …*

**Response:** Accepted. We will change the existing line to:

"…are located not at the tops of the bays that are normally most affected by meteotsunamis, but about 2 km from the tops."

*Figure 3 should be moved below in the text.*

**Response:** Accepted. The figure will be moved below in the text.

*Page 10: I suggest to use the full name of the monitoring stations instead of their abbreviation.*

**Response:** Accepted. Full names of the monitoring stations will be used instead of abbreviations.

*Lines 274-298: this part should be moved before (or at the beginning) of section 4.*

**Response:** Accepted. This part will be a part of a new methodology section introduced after the introduction section.

*Figures 6 to 10: please include labels for the transect's beginning and end (e.g. A and B) in maps and spectrograms or specify that all transects are plotted from the west to the east. It is unclear what's the transect number.*

**Response:** Accepted. It will be added that all transects are extracted from West to East.

*Lines 425-427 and 435-438: In both sentences, it's written that the ocean model fails in predicting meteotsunamis. As it is written it seems that the problem resides in the ocean model itself, while most of the uncertainty is associated with the atmospheric modelling of the meteotsunamigenic disturbance, as written in the subsequent phrases. I suggest reformulating the text in order to clarify that without accurate atmospheric predictions there are no chances to forecast meteotsunamis.*

**Response:** Accepted. "due to a shift in location of the modelled atmospheric disturbances" will be added to both sentences.