High-resolution operational NWP for forecasting meteotsunamis

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1 Introduction

Meteorological tsunamis [Monserrat et al.(2006), Vilibić et al.(2016)] are long-ocean waves generated by intense small-scale air pressure disturbances. The waves can be several metres high and cause substantial damage to coastal towns. The main objective of the MESSI project (Meteotsunamis, destructive long ocean waves in the tsunami frequency band: from observations and simulations towards a warning system) is to build a reliable prototype of a meteotsunami warning system.

A meteotsunami or meteorological tsunami is a tsunami-like wave of meteorological origin.

- 10% of tsunamis worldwide have unknown origin [Vilibić and Šepić(2017)]
- 3% already assigned to meteorological conditions such as: atmospheric gravity waves, pressure jumps, frontal passages, squalls ... [Šepić et al.(2016)]
- meteotsunamis hit coastlines around the world and have many local names: rissaga (Catalan), ressaca (Portuguese), milghuba (Maltese), marrobbio (Italian), abiki (Japanese), šćiga (Croatian)
- previous known events: the highest meteotsunami recorded so far was in Vela Luka (1978, 6m) in Croatia which caused considerable damage but no people died, while there were other events that did cause human cost, such as in Chichago (1954,3m), Nagasaki (1979,5m), Ciutadella (2006,4m), Daytona Beach (1992,3.5m) and there were events recorded in Australia, New Zealand, UK, France, and even Finland!
- High waves destroy coastlines, strong currents endanger marine traffic in passages and channels that lead to harbours, while sea trafic is also endangered due to reduced sea depth during low tide.
- These events are dangeorus, especially in areas where the tide amplitude is low. In Adriatic the tide amplitude is 0.5m so consequently the towns lay very low above the medium sea level (e.g. Vela Luka, Stari Grad, Mali Lošinj). Here are several links to videos:
- https://www.youtube.com/watch?v=y-QlJO0ChwA
- https://www.youtube.com/watch?v=lzA5DTk_vIg

Meteorological tsunamis result from several resonance mechanisms that amplify the wave at the ocean surface for several orders of magnitude. But the wave has to be generated at the sea surface by the propagating pressure disturbance. Atmospheric gravity waves will propagate in a stable layer (Richardson number $Ri < 0.25$) from surface up to about 500hPa if the layer above is unstable ($Ri > 0.25$). At the level about 500hPa there is a jet that can exceed 40m/s. Strong gradients there support the generation of atmospherc gravity waves. These waves would propagate upward if there was no unstable layer at 500 hPa and the wave energy would simply propagate vertically. If the unstable layer contains a a critical (steering) level in which the wind speed equals the propagation speed of ducted waves, then the waves become trapped in a stable atmospheric layer adjacent to the ground. If there was no critical level, the waves would be absorbed.

When an air pressure disturbance of several hPa in amplitude propagates above the sea surface at the speed of long ocean waves $c = \sqrt{gH}$ where g is gravity acceleration and H is ocean depth, the long ocean wave

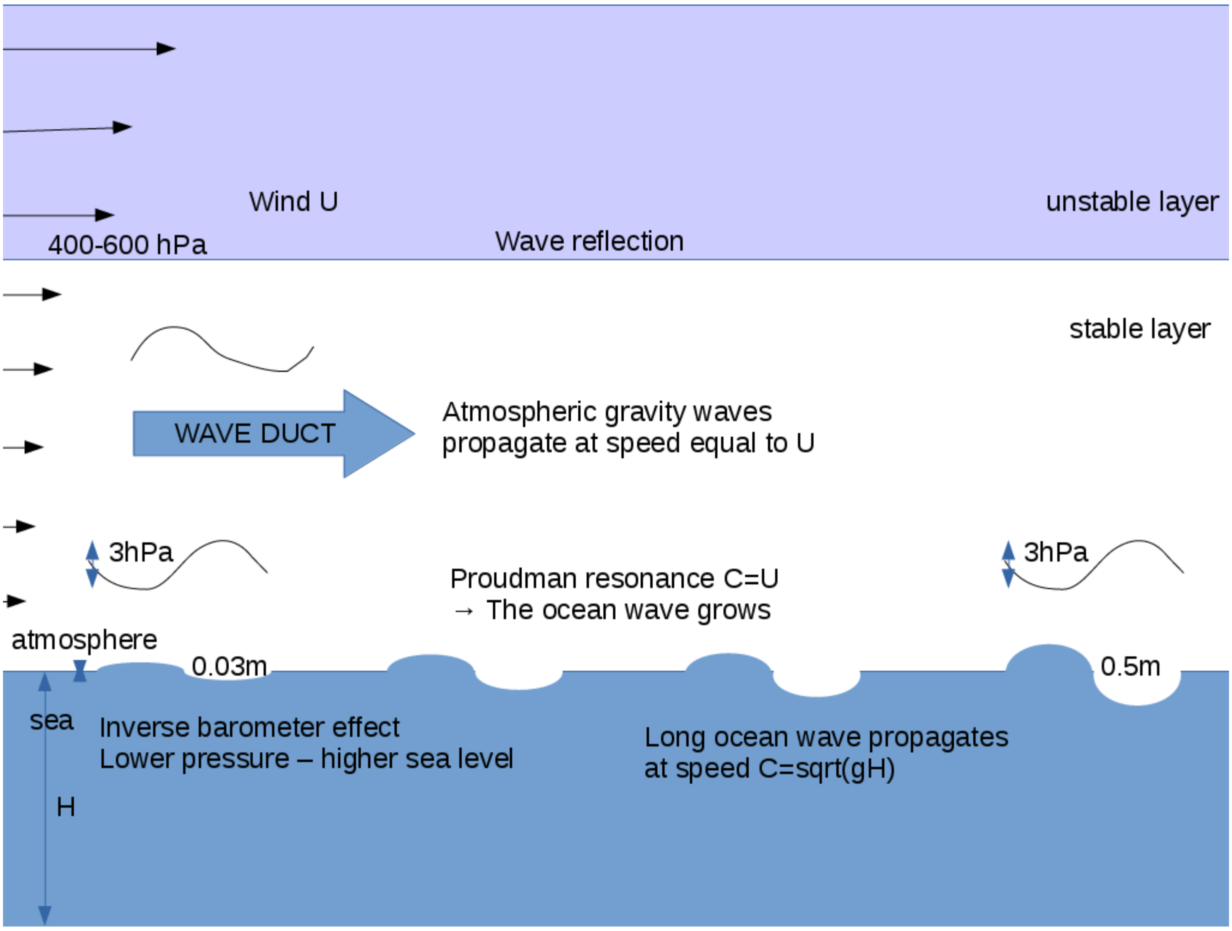

Figure 1: Illustration of the meteorological part in the meteotsunami generation processes. Atmospheric gravity waves are trapped below the unstable layer and propagate with speed U (equal to wind speed of unstable layer) as a duct wave. The wave in surface pressure generates a wave at the ocean surface due to inverse barometer effect (lower pressure - higher sea surface, higher pressure - lower sea surface). As the atmospheric wave moves (with the speed U), so does the wave at the ocean surface (with a speed of long ocean waves $C = \sqrt{gH}$*). If* $c = U$ *the wave grows due to Proudman resonance.*

amplifies due to Proudman resonance. Therefore, the meteorological model should predict the intensity, speed and direction of a fast and intensive pressure disturbance. The wave height at the open sea is on the order of centimeters but grows due to Proudman resonance (Figure 1). The ocean wave later amplifies due to shoaling when the wave slows down but the amplitude increases as the sea depth decreases (c in the above formula decreases with H). This increases the wave height up to one meter. Finaly, some harbours are particulatly vurnerable and amplify the wave to several meters. Incoming ocean waves can be amplified more than 100 times before hitting the coast as a destructive meteotsunami.

2 Meteorological conditions and model technicalities

Synoptic setting:

- Inflow of warm air from Africa 850 hPa
- SW jet > 20 m/s at 500 hPa

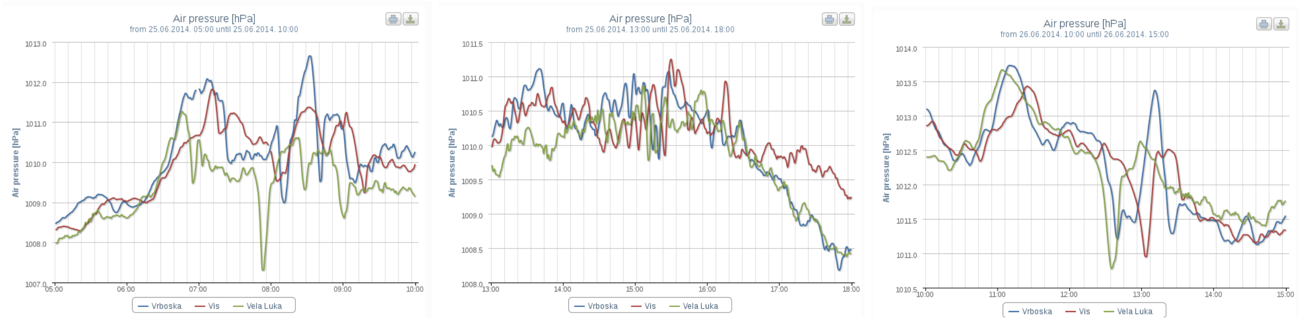

Figure 2: Air pressure measured on stations Vrboska (blue, Hvar island), Vis (red) and Vela Luka (green) with one second data interval during a widespread meteotsunami event on 25-26 June 2014, maintained by IOF .

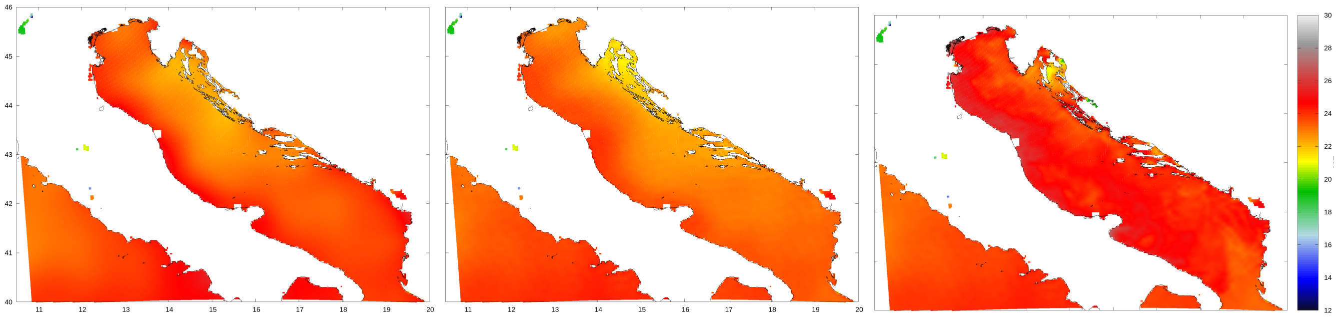

Figure 3: The SST in the operational forecast (left), when using SST from OSTIA (middle) and ROMS (right). SST influences the stability of the lower portion of the troposphere and the possibility of generating and propagating pressure disturbances.

- Unstable layer (Ri<0.25) 400-600 hPa
- High resolution: Forecasting a pressure change of more than 1hPa/1min
- Model output every minute is needed in order to detect the rapidly moving pressure wave (Figure 2).

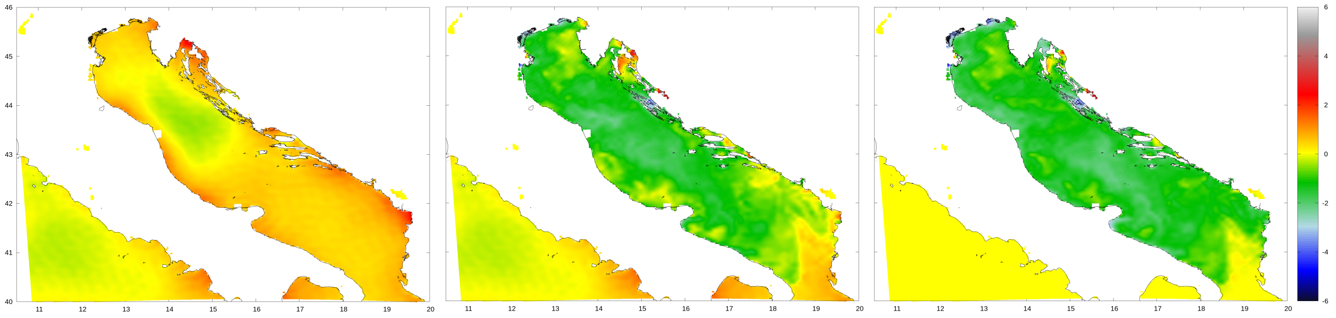

Figure 4: The differences between SSTs: in the operational forecast minus OSTIA (left), OPER-ROMS (middle) and OSTIA-ROMS (right). In this case, ROMS is warmest above open sea and consequently lower layers of troposphere are less stable.

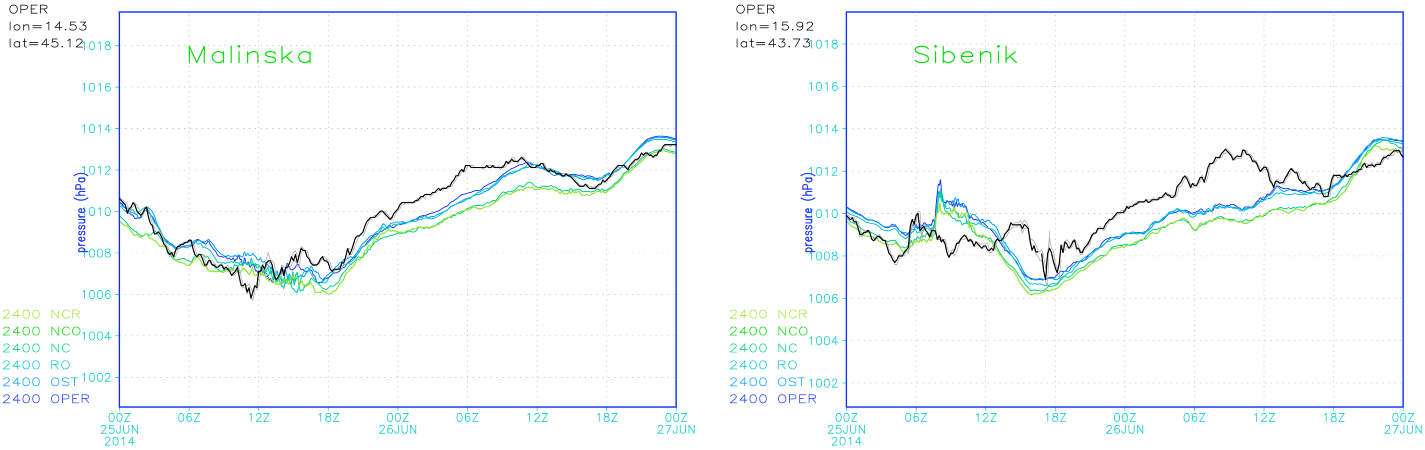

Figure 5: Figures show measured pressure (black line, 10 min interval) and output every time step (1 min) from operational run and experiments using SST from OSTIA and ROMS, new surface representation alone and in combination with ROMS. Both SST and roughness of the surrounding land surfaces influence the development, intensity and location of high frequency oscillations in pressure. OPER old topography and z0 IFS SST, OST using OSTIA SST, RO using ROMS SST, NC new topography and z0, NCO new topo + OSTIA SST, NCR new topo + ROMS SST.

- The atmospheric model should predict the pressure disturbance moving in the right direction (for Adriatic, the direction of SW jet at cca 500hPa) and at the right speed (speed of SW jet) and at the right position in space and time (if this is to be useful further).

Atmospheric numerical weather prediction models represent one of the main components of any meteotsunami warning system. The non-hydrostatic 2km resolution ALADIN forecast is running operationally in Meteorological and Hydrological Service of Croatia since July 2011. The suite predicts propagating small-scale pressure disturbances capable to excite meteotsunamis. However, the comparison of forecast pressure evolution to the measured data shows that the intensity of the observed pressure disturbances is simulated fairly by the model, but at a slightly different position and time, and propagate with slightly different speed and direction. Meteotsunamis are known to be highly sensitive to these parameters.

One-minute model time-step is used for reproducing the disturbances. This allows for an accurate estimate of the error in the position, shape, variability in space and time, speed and direction of the model disturbances with respect to those known to have generated meteotsunamis. We have further tried to improve the operational forecast by using of more realistic SST, e.g. coming from the ROMS ocean model [Janeković et al.(2014)], and more realistic physiography of the terrain surrounding the Adriatic sea.

3 Experiments with different SSTs and z0 for one particular meteotsunami event

The recent meteotsunamis are investigated using available atmospheric data and meso-scale atmospheric model ALADIN with ALARO physics package. ALADIN model is used for reproduction of travelling air pressure disturbances during the Adriatic meteotsunami event.

Here we analyse a widespread meteotsunami event on 25-26 June 2014 [Šepić et al.(2016), Šepić et al.(2016)]. The sea surface temperature (SST) used in the model forecast arrives from the global model that is used for

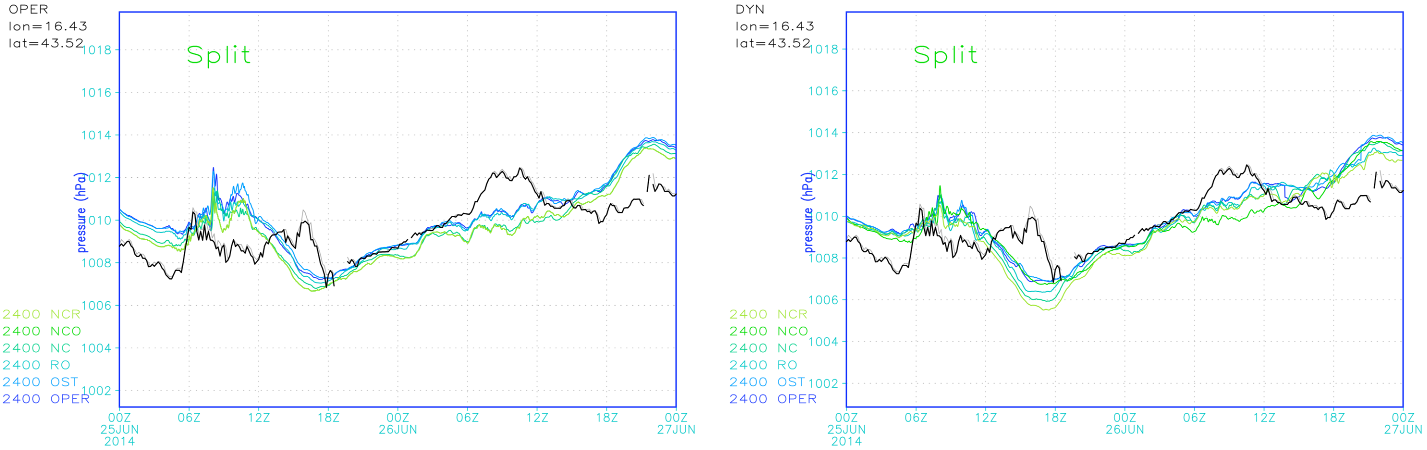

Figure 6: As Figure 5 but for Split (left) and using different dynamics set-up (right). OPER old topography and z0 IFS SST, OST using OSTIA SST, RO using ROMS SST, NC new topography and z0, NCO new topo + OSTIA SST, NCR new topo + ROMS SST.

lateral boundary conditions. It has been shown that model SST can be quite far from real values over the Adriatic, especially over the coastal areas, such as in the WAC and Kvarner bay (Figure 3. The use of more realistic SST, from OSTIA analysis and the ROMS ocean model influences the intensity and propagation of the pressure disturbance. Recently, it has been shown that the physiography fields used by the model are of too low resolution and contain errors in the Adriatic area. More realistic physiography of the terrain surrounding the Adriatic sea affects the triggering of the disturbance (Figure 5). Different dynamics set-up does affect the amplitude of the pressure wave (Figure 6) as well as the evolution of larger scale pressure features.

4 Conclusions

If the large scale setting (synoptic scale) is forecasted by the large scale model, then the small scale LAM generates atmospheric gravity waves. The wave trapping of the propagating wave depend on the existence of unstable layer at about 500 hPa and a stable layer below and a critical level in the unstable layer. The local manifestation of the pressure wave is sensitive to many factors. SST influences the stability of the lower portion of the troposphere and the possibility of generating and propagating pressure disturbances. In this case, ROMS is warmest above open sea and consequently lower layers of troposphere are less stable.

5 References

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