ABNORMAL OSCILLATIONS OBSERVED IN BOOTHBAY AND OTHER LOCATIONS ALONG THE MID COAST OF MAINE ON 28th OCTOBER 2008. OCEAN AND GROUND METEOROLOGICAL DATA ANALYSIS.

Unusual high frequency sea level oscillations were reported along the mid coast of Maine, USA, on October 28th, 2008. Significant oscillations were observed around 3 pm in Boothbay Harbor, Southport and Bristol. Eye-witness reported rapid water level changes as much as 4 m during the event with strong associated currents that damaged piers and boats in some harbors in the area.

No tide gauge was deployed in the affected harbors to allow a quantification of the reported phenomenon. Given the general characteristics of the observed oscillations and that no earthquakes were detected in the area at the time of the sea level oscillations, it is suggested that this event could be considered as a meteotsunami. In the following this hypothesis is further investigated.

Despite no data are available at the spots where larger oscillations were reported, a number of tide gauges and atmospheric pressure sensors are deployed in the area. The positions of the instruments we consider for this analysis are shown in Fig. 1 and Table 1.

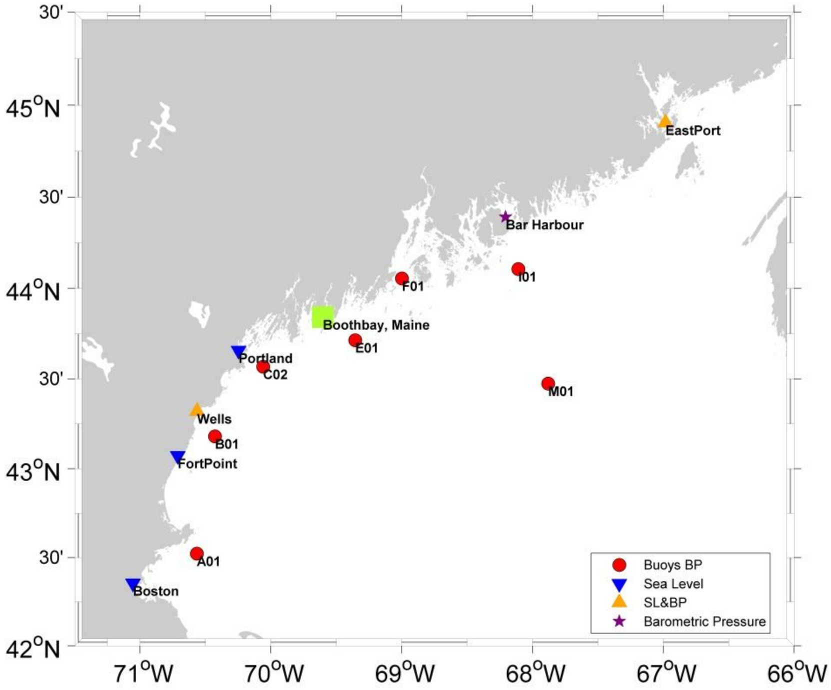


Fig. 1- Data available. Buoys with atmospheric pressure sensors are shown by red circles; tide gauges are plotted using blue triangles; spots where tide gauges and atmospheric pressure registers are available are represented by orange triangles; and coastal points with only atmospheric pressure are shown with purple stars. Boothbay harbor is identified in the map by a green square.

Place	Longitude / Latitude	Sampling Interval	Data Source	Type
Boothbay	69°36’08.56” W / 43°50’29.22” N	------------------	---------	-----------
EastPort	66°58’58.44” W / 44°54’16.56” N	1 min	CO-OPS	S.L. & A. Pressure
Wells	70°33’47.88” W / 43°19’12.00” N	6 min		
Portland	70°14’58.12” W / 43°39’24.12” N	1 min	CO-OPS	Sea Level
FortPoint	70°42’42.12” W / 43°04’18.12” N	6 min		
Boston	71°03’12.24” W / 42°21’17.28” N	1 min		
Bar Harbour	68°12’18.00” W / 44°23’30.12” N	6 min	CO-OPS	Atmos. Pressure
M01	67°52’47.40” W / 43°28’26.40” N	10 min	GOMOOS	
I01	68°06’31.20” W / 44°06’12.00” N			
F01	68°59’52.20” W / 44°03’15.00” N			
E01	69°21’18.60” W / 43°42’51.60” N			
C02	70°03’30.00” W / 43°34’03.60” N			
B01	70°25’37.80” W / 43°10’48.00” N			
A01	70°33’55.20” W / 42°31’21.60” N			

CO-OPS→ Center for Operational Oceanographic Products and Services.
GOMOOS→ Gulf of Maine Ocean Observing System.

Table 1- Position of the points where data is available and its type.

The signal at tide gauges deployed along the coast is entirely dominated by tides but some high frequency abnormal fluctuations become evident when tides are subtracted from raw data. These high frequency oscillations are observed in Portland ME, Fort Point NH, Boston MA, and Wells ME in the afternoon/evening of 28th October (see Fig. 2 for two days sea level records).

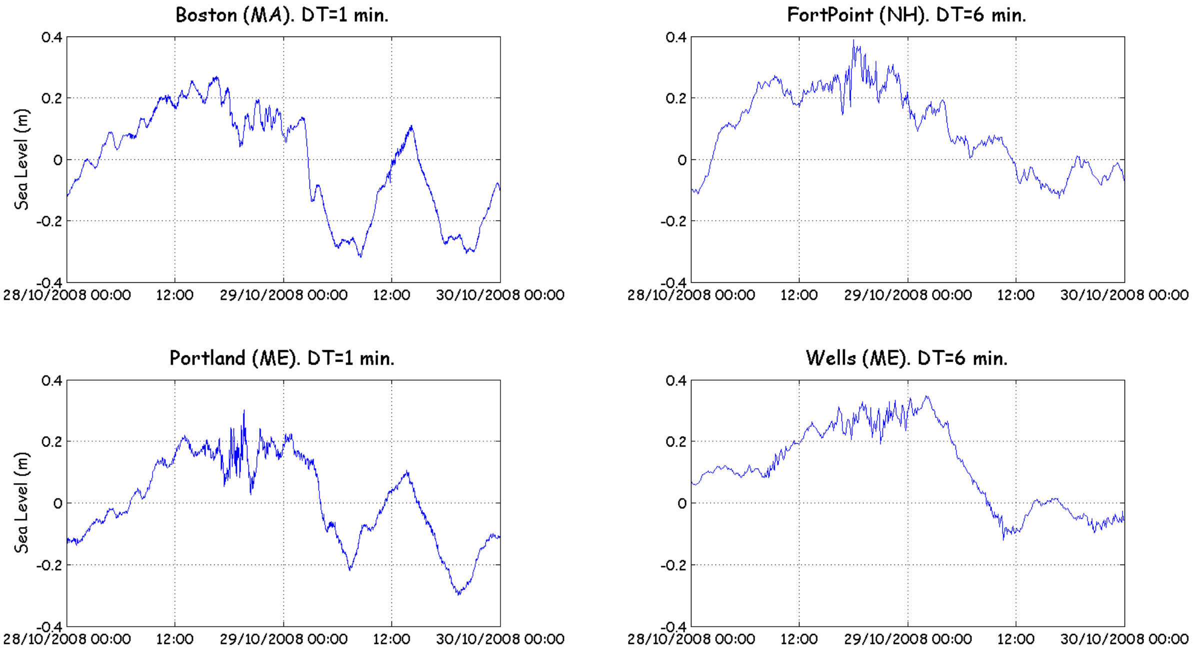


Fig. 2- Sea level residuals after tides have been removed from raw data at Boston, MA, FortPoint, NH, Portland, ME and Wells, ME.

A small signal is also suggested in Eastport ME, although this instrument is perhaps too away from the affected area to be affected by the largest oscillations (Fig. 3).

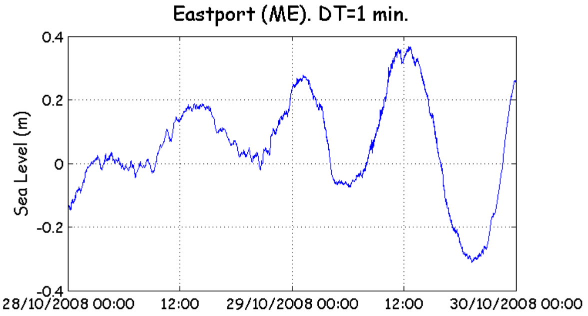


Fig. 3- Sea level residuals after tides have been removed from raw data at Eastport, ME.

In the highest frequency band, in the order of minutes, oscillations related to the observed phenomenon become even more evident (Fig. 4). Here the time span is extended to one week and the data was high pass filtered using a one hour running average. In addition to the already mentioned high frequency oscillations on 28th October, very similar rapid sea level changes become also evident in Portland in the morning of 26th October although of slighter smaller amplitude. These oscillations are also recorded in Wells and for this location they are even larger than those observed on 28th.

High frequency sea level record at Wells displays a periodic (12 hours) sea level pulse that is not observed at other locations. This pulse seems to be the responsible of the large energy observed on 26th in comparison with 28th at Wells and will be further investigated later on in this study.

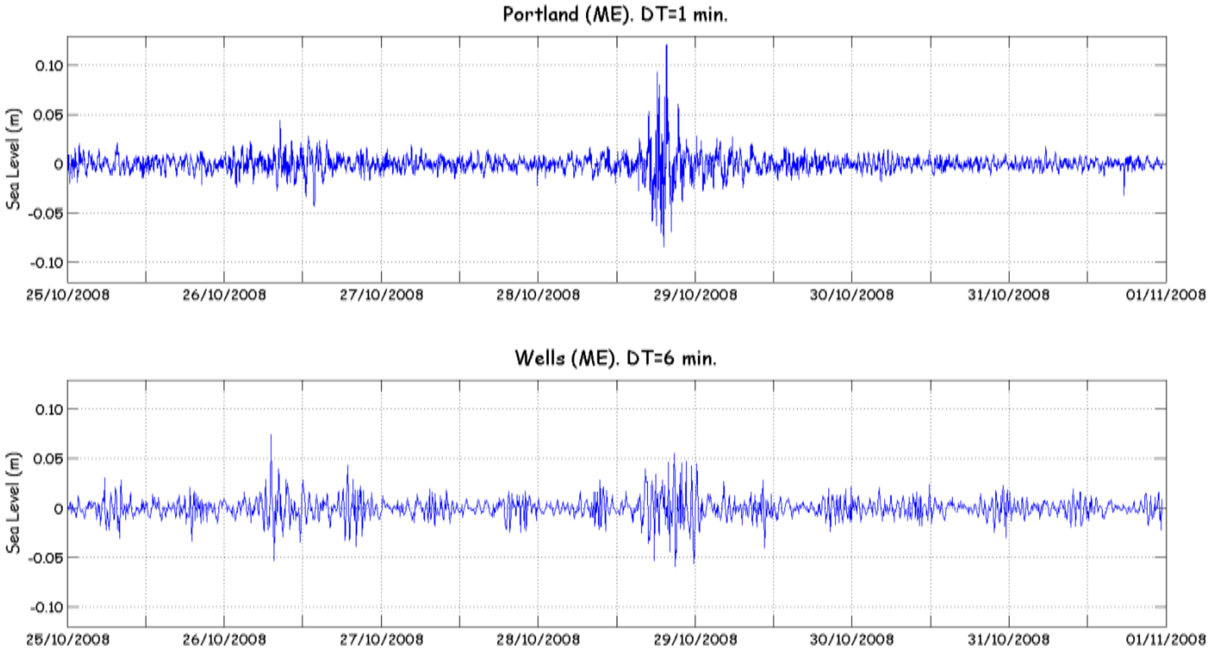


Fig. 4- High-pass filtered sea level data at Portland, ME and Wells, ME. An hour running average has been used to remove low frequency oscillations.

The abnormal high frequency oscillations clearly identified in the available tide gauges and observed simultaneously to the large amplitude oscillations reported in some specific spots along the coast where data are not available suggest that high frequency sea level energy is present in the whole area during the observed event. This energy is surely further resonantly amplified in some specific inlets or harbors due to their particular topography and is the cause of the large amplitude reported sea level changes. Ocean energy did not come from any seismic activity in the area. The energy source is probably coming from the atmosphere. In the following this hypothesis will be examined by analyzing simultaneous atmospheric pressure records.

Indeed, atmospheric pressure records available in the area show a high frequency energy increase simultaneously to the observed sea level oscillations, although only those instruments with sufficient high temporal resolution are able to catch these features. Actual pressure data recorded from 00h00 at 28th to 00h00 at 30th October, 2008 and the same data after being filtered to retain those periods shorter than 5 hours are shown in Fig. 5. Abnormal high frequency oscillations become apparent in those instruments with sampling interval of 10 and 6 min. Those instruments with sampling interval of 1 hour are completely useless for this study.

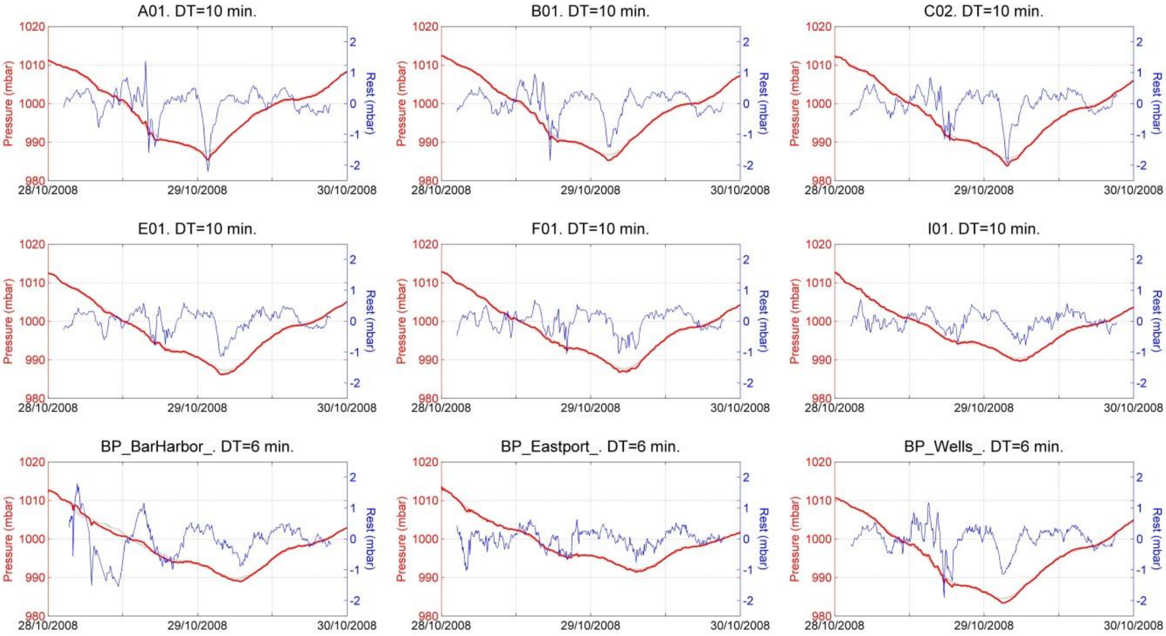


Fig. 5- Raw atmospheric pressure data (red) and high pass filtered data (blue). A running average of five hours has been used to remove low frequency oscillations.

A very similar behavior is observed in all the stations (red line) and even the high pass filtered data present the same general aspect. In order to better investigate the presence of abnormal high frequency fluctuations, the signals are further high pass filtered (1 hour) and extended to one week (some selected stations are shown in Figure 6). It is clearly observed that intensification of high frequency oscillations in the atmosphere coincides with observed high frequency sea level changes, in the afternoon of 28th October, when dangerous waves were reported in some areas, and also in the morning of 26th, when no dramatic waves were reported but some signal has also been observed in tide gauges.

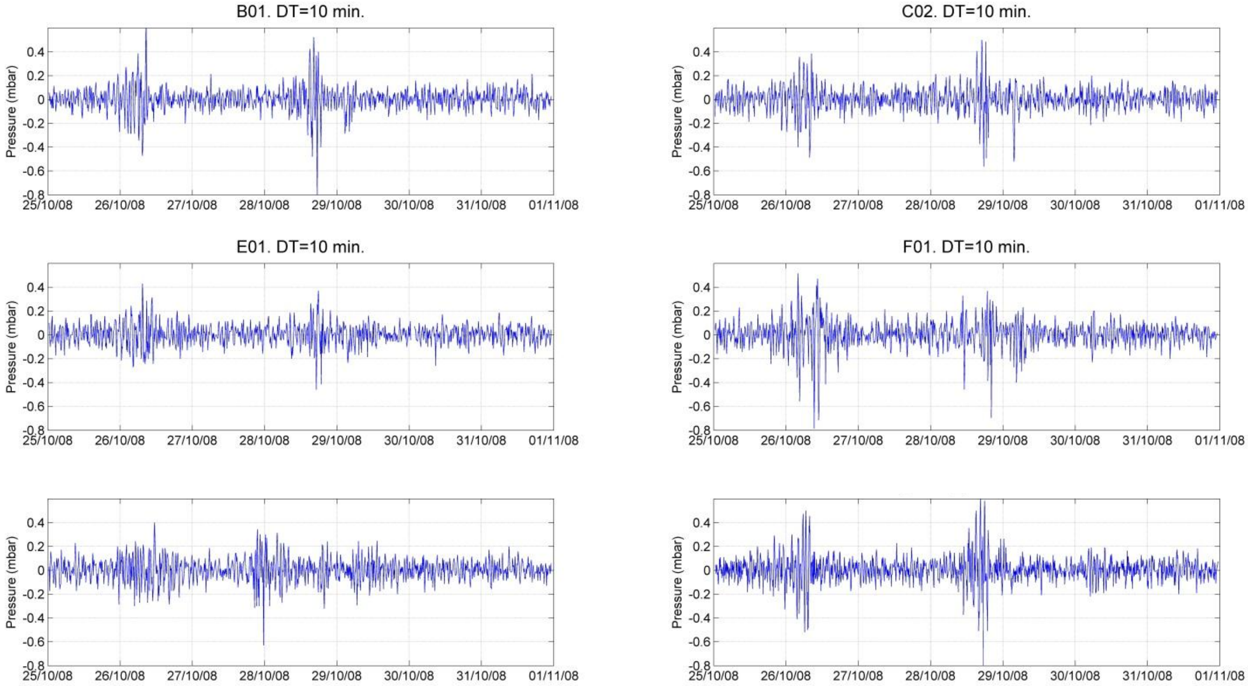


Fig. 7- High pass filtered atmospheric pressure data using an hour running average.

In order to provide a better comparison analysis between sea level and atmospheric pressure we concentrate in Wells, ME, where high frequency (6 min time sampling) atmospheric and sea level data are available at the same location and in Portland, where the largest sea level oscillations have been measured. As no atmospheric pressure is simultaneously recorded in Portland, we use for comparison the nearest available buoy (C02). The simple visualization of filtered data shows a simultaneous atmospheric pressure and sea level energy increase. (Fig. 6a & Fig. 7b).

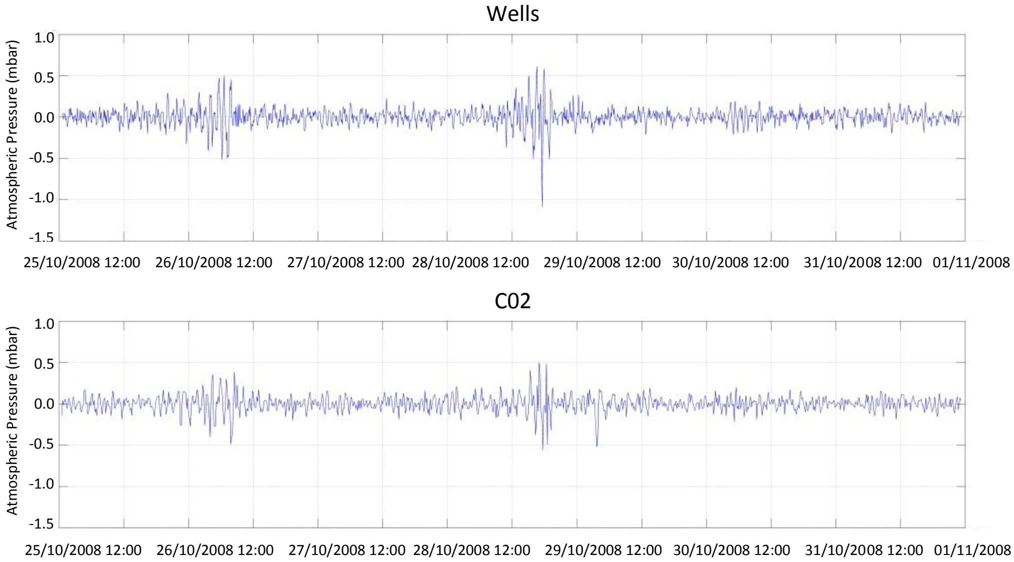


Fig. 6a- High frequency oscillations in atmospheric pressure in Wells barometer and C02, the closest buoy to Portland.

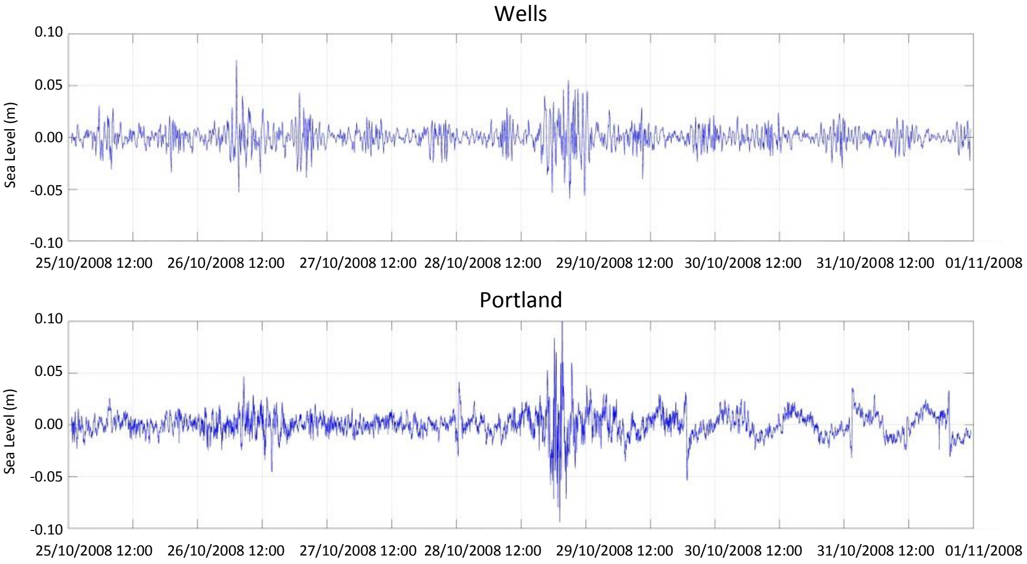


Fig. 7b- High frequency oscillations in sea level in Wells and Portland tide gauges. This high frequency sea level oscillations are simultaneous with the atmospheric pressure oscillations shown in *Fig. 6a*.

As the strength of meteotsunamis has been better correlated with atmospheric pressure tendency rather than atmospheric pressure variations, the rates of pressure change are for the two stations closest to Boothbay and Portland are also plotted in Fig. 8. It becomes evident how atmospheric pressure tendency rapidly increase during the episode in both locations. However, the largest computed values are 0.05 mbar/min at E01 and 0.10 mbar/min at C02; which are small in comparison with previously reported rates of change which have led to strong meteo-tsunamis events in the Mediterranean (Šepić and Vilibić 2011).

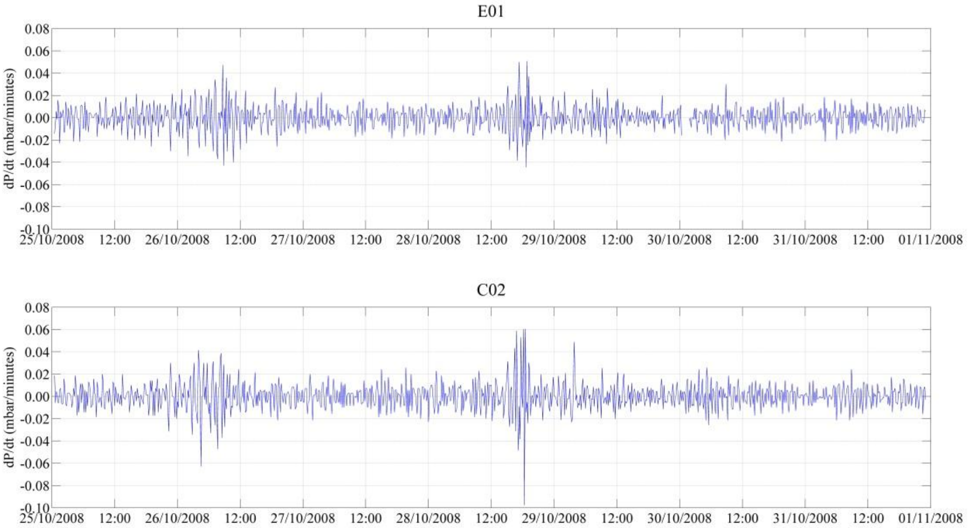
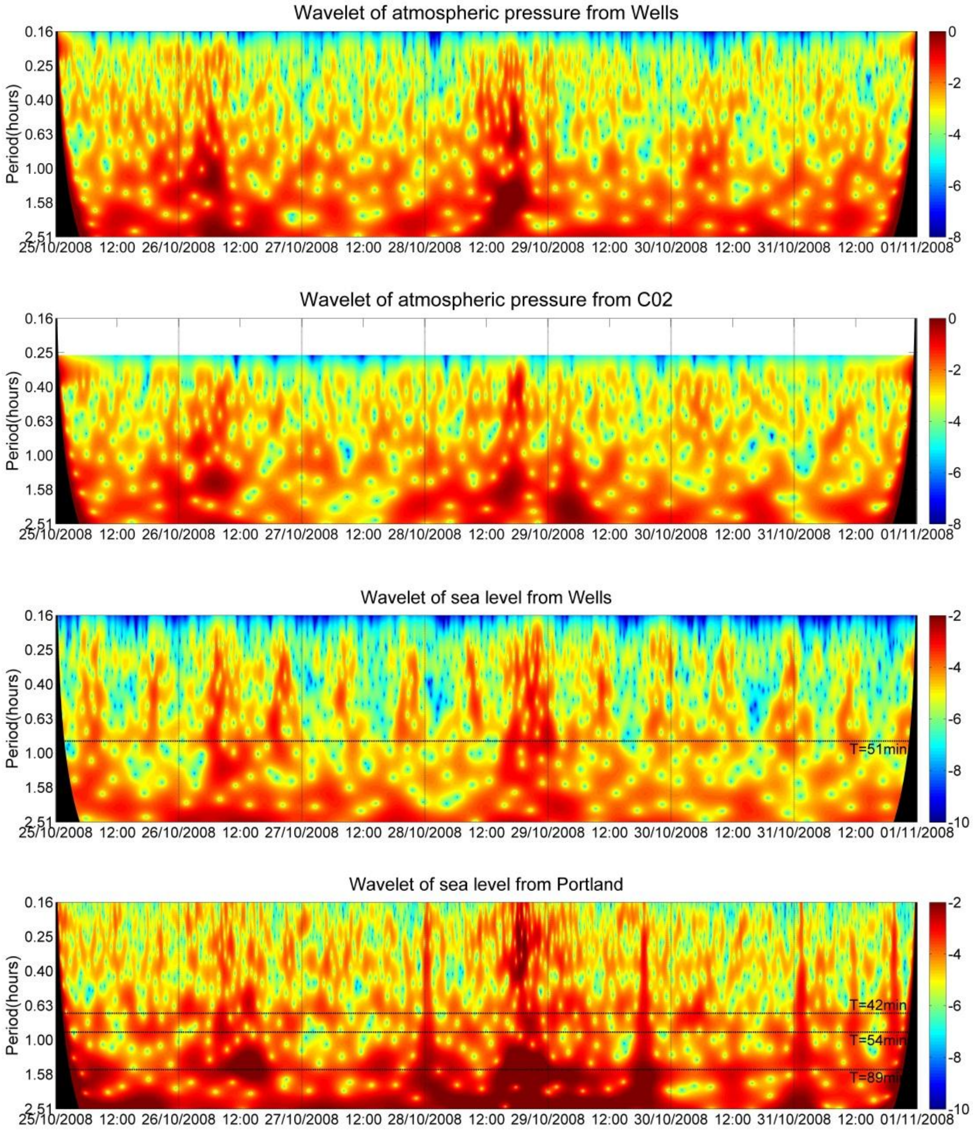


Fig. 8- Pressure tendency over time from buoys E01, the closest to Boothbay, and C02, the nearest to Portland.

The time evolution of energy contents in both the atmosphere and the ocean is further investigated by means of wavelets. Computed spectrum for sea level at Wells (not shown) has a clear peak suggesting a dominant seiche response of about 51 min. Portland spectrum (neither shown) is rather more complicated with several peaks at 42, 54 and 89 min. These peaks are marked in the wavelet plots (Figure 9). Wavelet analyses clearly show that seiche oscillations at both locations are amplified when an increase in atmospheric pressure energy also occurs. This increase in atmospheric energy is not concentrated in a given frequency but the whole frequency band suffers a similar amplification. Results from wavelets suggest a cause-effect relationship between high frequency energy of the atmospheric pressure and seiche activity in the harbors.


Wavelet of atmospheric pressure from Wells

Wavelet of atmospheric pressure from C02

Wavelet of sea level from Wells

Wavelet of sea level from Portland

Fig. 9- Wavelets from atmospheric pressure at Wells and C02 buoy (the nearest from Portland) and sea level at Wells and Portland.

In Wells harbor other additional factors must be considered to explain the relationship between atmospheric pressure activity and seiche oscillations which seems to be more evident for Portland. An interesting clear 12 h pulse in the seiche response of Well harbor seems to be evident with seiche energy increases during low tides (Figure 10). This particular behavior masks the cause-effect relationship between atmospheric pressure and sea level mentioned above.

The observed pulse is not a feature restricted to this week of data but it is observed all along the year.

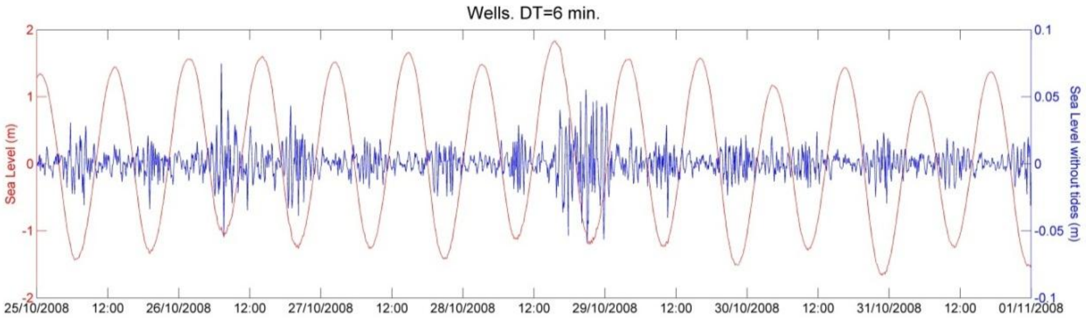


Fig. 10- High frequency sea level oscillations in Wells (blue) and computed tides (red).

The reason for this pulse is surely related to the particular geometry and bathymetry of the area which is the responsible of a significant change in the resonance amplification during low and high tide. Topography around Wells tide gauge is rather complicated (Figure 11). The surrounding terrain is dominated by marsh getting inundated with high tides (Figures 12 and 13). Even without any additional numerical computation (suggested), these changes seem to be enough to explain why seiches become stronger during low tides.

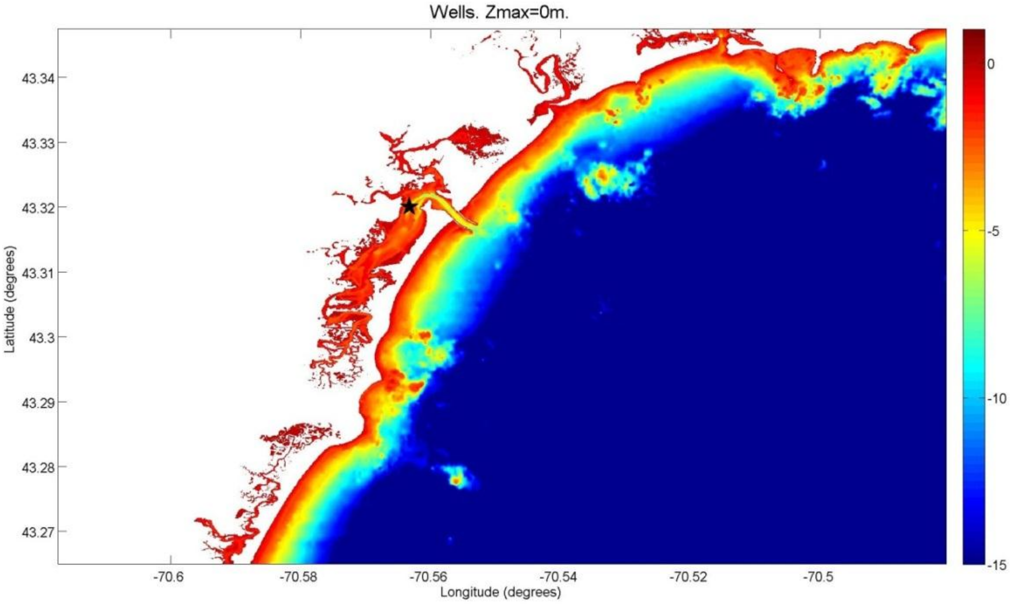


Fig. 11- Bathymetry of Wells from http://www.ngdc.noaa.gov/dem/squareCellGrid/download/606. Depth (m) are represented in colors.

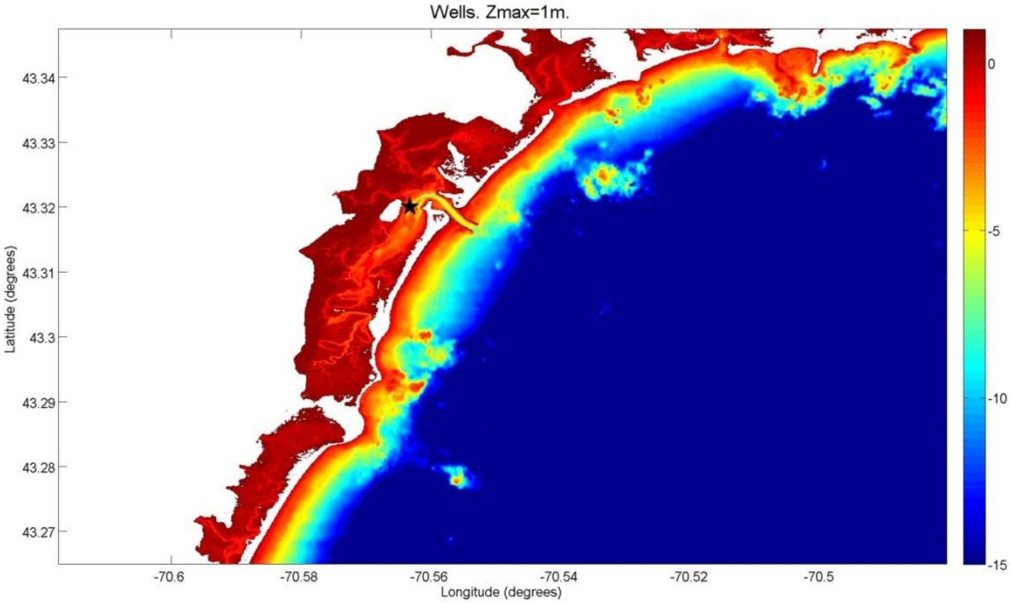


Fig. 13- As Fig. 11 but adding 1m of water approximately corresponding to high tides.

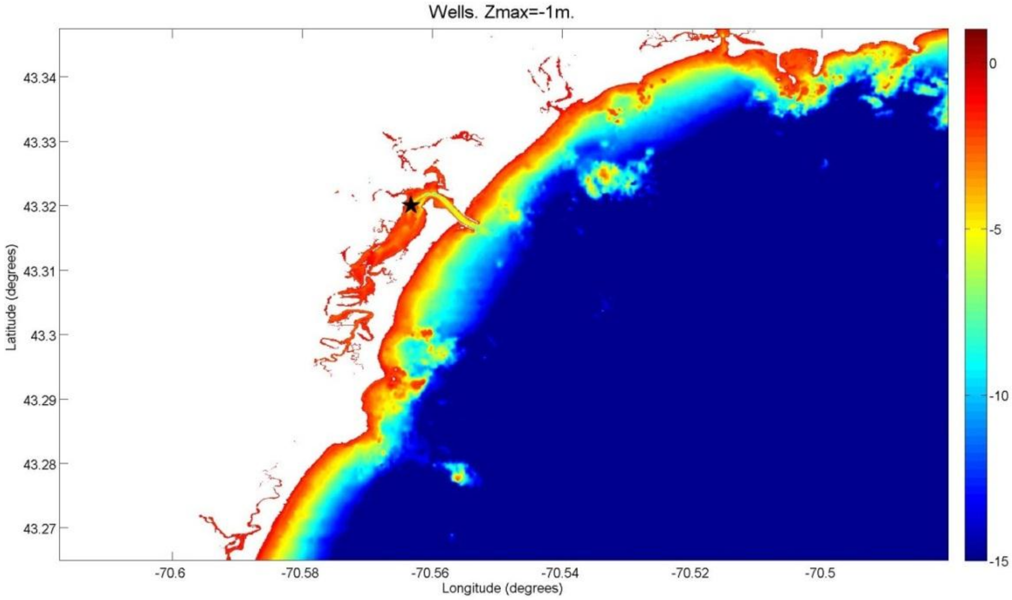


Fig. 12- As Fig. 11 but subtracting 1m of water approximately corresponding to low tides.

Resonant characteristic of Wells are not particularly strong and this effect has no dramatic consequences at this harbor, but this clearly observed change between low and high tide demonstrates how tidal regime should not be completely neglected when analyzing other resonance responses.

Despite atmospheric data in the region have not enough resolution to properly catch the high frequency atmospheric wave properties showed before, an effort was made to analyze the available data with the aim of obtaining the general characteristics of the atmospheric waves responsible for the target event. To do so, the methodology developed by (Monserrat and Thorpe 1992)and successfully applied to other regions was followed. A triangle of instruments (hereinafter referred to as triangle 0) was selected to obtain the atmospheric wave speed and direction at least of the longest period waves.

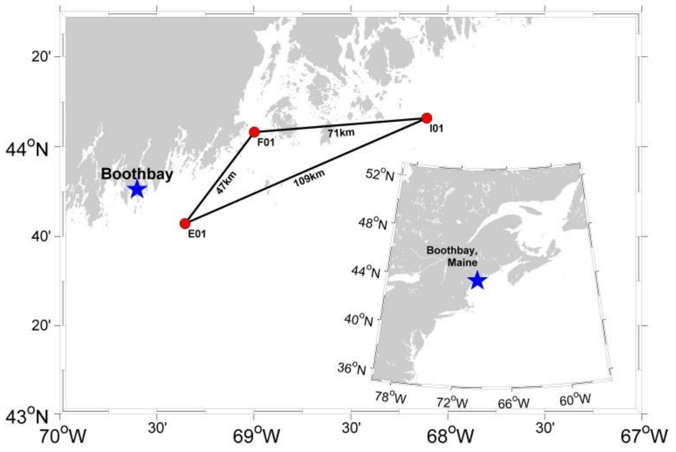


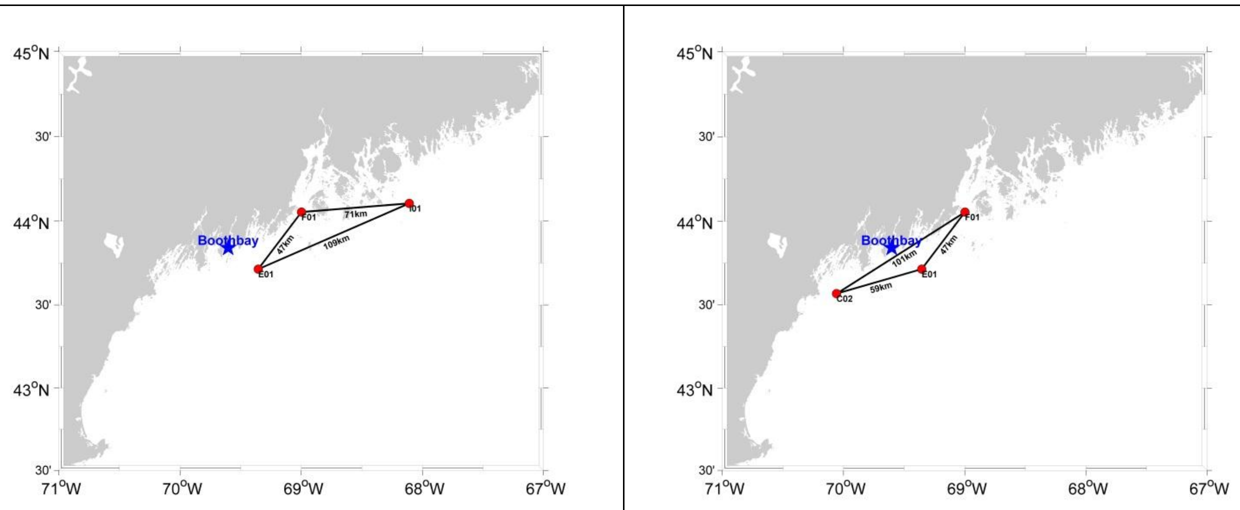
Fig. 14- Triangle of atmospheric pressure gauges used for this study.

When correlation between stations is computed using the two days raw signals (red curves in Figure 5) from 00h00 on 28th to 00h00 on 30th, lags of maximum correlation are found to be zero. This means that observed wave trough simultaneously affects the whole area.

When data are high pass filtered retaining only those oscillations with periods less than 5 hours (blue curves in Figure 5) the computed lags of maximum correlation indicate that the atmospheric waves move with a phase speed of 24 m/s and a direction of 286º, i.e., travelling from the SW to the NE.

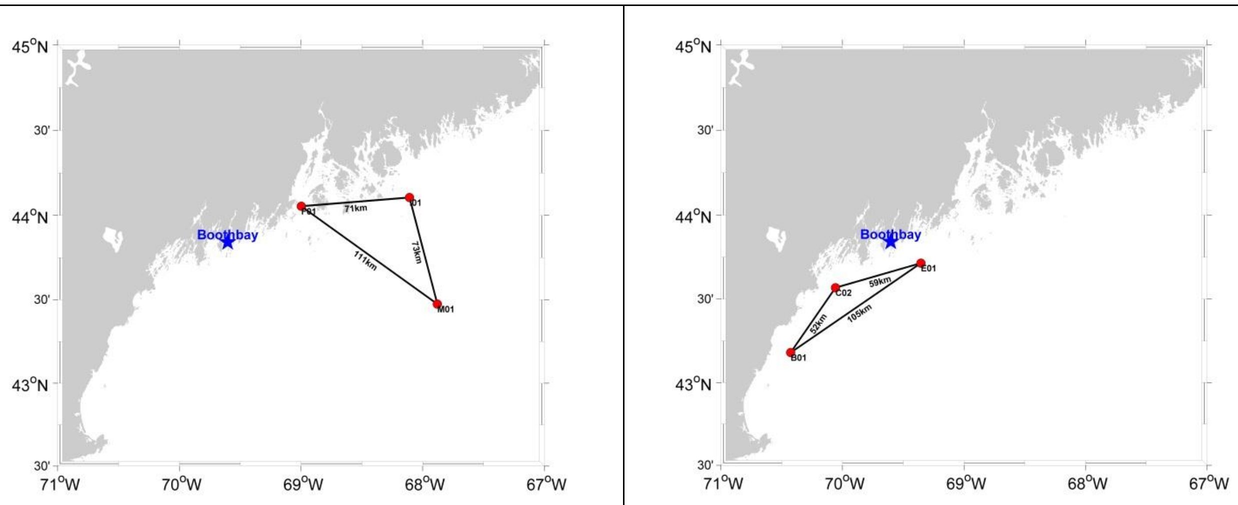
When the data are further filtered to retain only those oscillations of the order of minutes, the correlations found between stations are not good enough to be able to compute the atmospheric wave characteristics. This is because the distance between stations is too long and the time sampling is too coarse to properly analyze these high frequency perturbations.

The atmospheric waves are further investigated using additional atmospheric stations. Other triangles of ground meteorological stations were constructed around Boothbay to infer the atmospheric wave properties (Figure 15).



Triangle 0

Triangle 1



Triangle 2

Triangle 3

Fig. 15- Triangles of atmospheric pressure gauges used for this study.

Results obtained with the four triangles using atmospheric pressure observations filtered to keep only those periods above 5 h are listed in Table 1. Only two triangles fulfill the quality requirements to provide a reliable phase speed and wave direction; however, results are not consistent (Table 2).

	Trian. 0	Trian. 1	Trian. 2	Trian. 3
c (m/s)	23.67	37.65	-	-
α (°)	286.01	247.54	-	-

Table 2- Phase speed and direction of propagation obtained with the different four triangles using filtered data below 5 hours.

When the frequency window is slightly increased retaining periods below 12 h results are improved (Table 3).

	Trian. 0	Trian. 1	Trian. 2	Trian. 3
c (m/s)	29.48	26.61	23.80	24.01
α (°)	274.59	255.83	94.62	214.18

Table 3- Phase speed and direction of propagation obtained with the different four triangles using filtered data below 12 hours.

On the other hand, when correlation between stations is computed from 00h00 on 26th to 00h00 on 28th, to compute atmospheric pressure properties for the first, less energetic, observed event, lags of maximum correlation do not fulfill the quality criteria and no wave property can be found even when periods less than 5 hours or less than 12 hours are retained.

It is concluded that, in order to infer the atmospheric wave characteristics with periods of the order of minutes from ground meteorological stations, it is needed a smaller triangle (i.e. closer stations) and a time sampling interval of one minute or less. The available data simply suggest that perturbations of the order of several hours seem to travel above the region with phase speeds of about 24-29 m/s and with a direction of propagation of 220-290 degrees.

Conclusions

The analysis of the available data in the area suggest that the large sea level oscillations observed in Boothbay harbor and other inlets along the mid coast of Maine, USA, on October 28th, 2008 correspond to meteotsunamis. Rapid atmospheric pressure fluctuations traveled over the area from the southwest to northeast with a speed of about 24-29 m/s transferring their energy to the open ocean, which was later resonantly amplified at some given spots.

Available atmospheric data are not of enough spatial and temporal resolution to properly catch the atmospheric wave properties. In order to compute the properties of the atmospheric waves in the order of minutes it is needed a smaller triangle of meteorological stations with a time sampling interval of better time resolution (ideally 1 min).

A similar sea level energy increase was also observed on 26th, October in the region examined. It seems that these perturbations did not produce comparative damage at the hot spots despite they are reflected at the sea level records at the available stations. The reason should be further investigated.

Wells station presents a very peculiar behavior, with a clear seiche increase during low tides. It is suggested that the reason is related to the dramatic bathymetric changes from low and high tides at this location as it is surrounded by a very low-lying area. This fact has no important consequences at this spot but this result suggests that the tidal regime should be taken into consideration when analyzing strong resonant seiches.

References.

Monserrat, S., and A.J. Thorpe. "Gravity-wave observations using an array of microbarographs in the Balearic Islands." *Q. I. R. Meteorol. Soc.* 118 (1992): 259-282.

Šepić, J., and I. Vilibić. "The development and implementation of a real-time meteotsunami warning network for the Adriatic Sea." *Nat. Hazards Earth Syst. Sci.* 11 (2011): 83-91.

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