Report on events 1, 6 and 7 of documented potential meteotsunami events: preliminary analysis of tide gauge data

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28 March 2012

Introduction

The objective of this report is to document some characteristics of potential meteotsunami events 1, 6 and 7, visually being the most interesting and the strongest of all 9 potential meteotsunami events extracted from tide gauge records between 2005 and 2011. Spectral and cross-spectral analyses have been applied on 1-min sea level data, in order to document significance of the oscillations in frequency domain, their outreach and coherence. Finally, we applied a simple analytical model used in previous studies of similar phenomena, and compared our observations with the theory.

All sea level time series have been detided and high-pass filtered to keep periods shorter than 6 h. Then the spectral analysis has been performed for each station which contained noteworthy sea level oscillations observed during events 1, 6 and 7. The spectra have been performed using 2048 points length KB window, 75% overlapped, over five-day periods (7200 point). Following Marcos et al. (2009), we computed separately event and background spectra, the latter by choosing calm intervals aside the events. Also, event-to-background spectral ratio are estimated, in order to separate local topographic effects from the energy of incoming ocean waves. Cross-spectra, coherence spectra and phase shift spectra have been computed between pairs of stations, in order to investigate the standing or propagating nature of the observed oscillations.

Analysis of events 1 and 7

The following stations are studied for events n°1 and 7 (Fig. 1): Montauk, Sandy Hook, Atlantic City, Cape May, Lewes, and Ocean City.

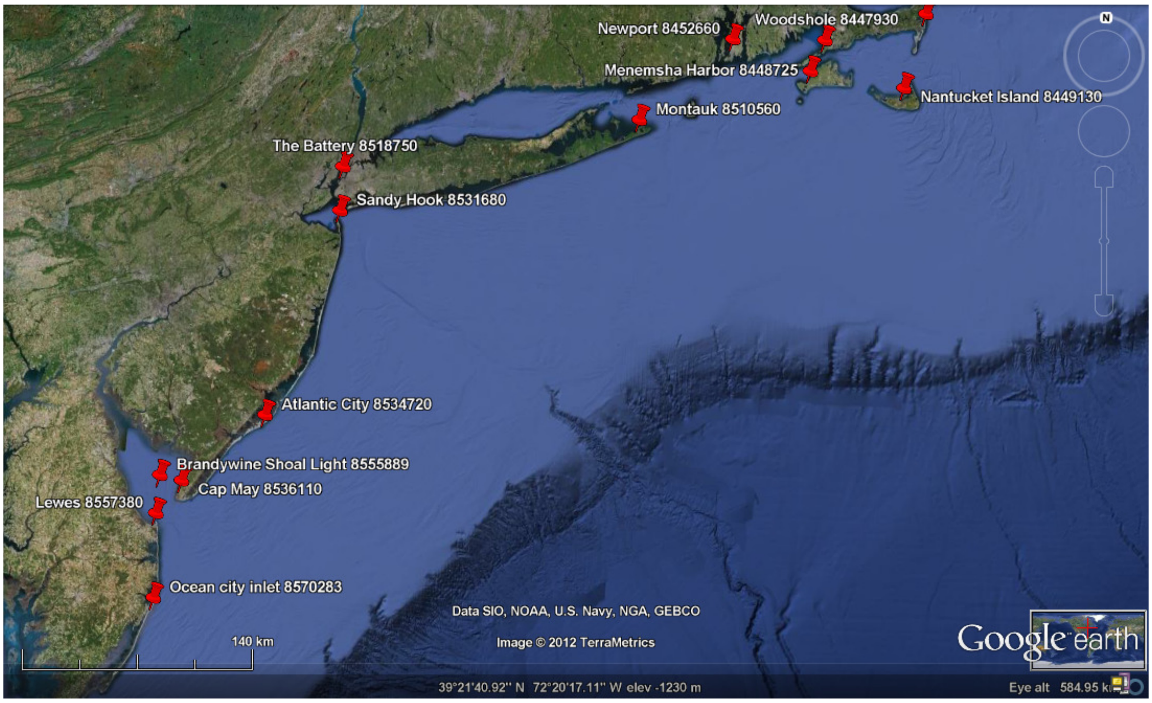


Figure 1. Location of tide gauge stations used for analysis of events 1 and 7.

Event 1

During event 1, the strongest sea level signal has been found at Atlantic City and Sandy Hook, where trough-to-crest values reached 85 cm and 45 cm, respectively (Fig. 2). Oscillations became apparent during the morning of 5 March 2008, between 6 am and 12 am, depending of the station. These oscillations started to slowly disappear on 6th after 6 am. Normally three strong waves have been observed at each station, followed by some decaying oscillations. At first sight, these oscillations have roughly 5 h periods, with some higher frequency waves superimposed. Also, it is apparent that these oscillations are not in phase. Namely, sea level begins to increase on 6 am at Atlantic City, whereas at Sandy Hook, Lewes, Ocean City and Montauk the increase begins at 6 am, 9 am, 8 am 11 am, respectively. Also, the Atlantic City and Sandy Hook records are clearly out of phase.

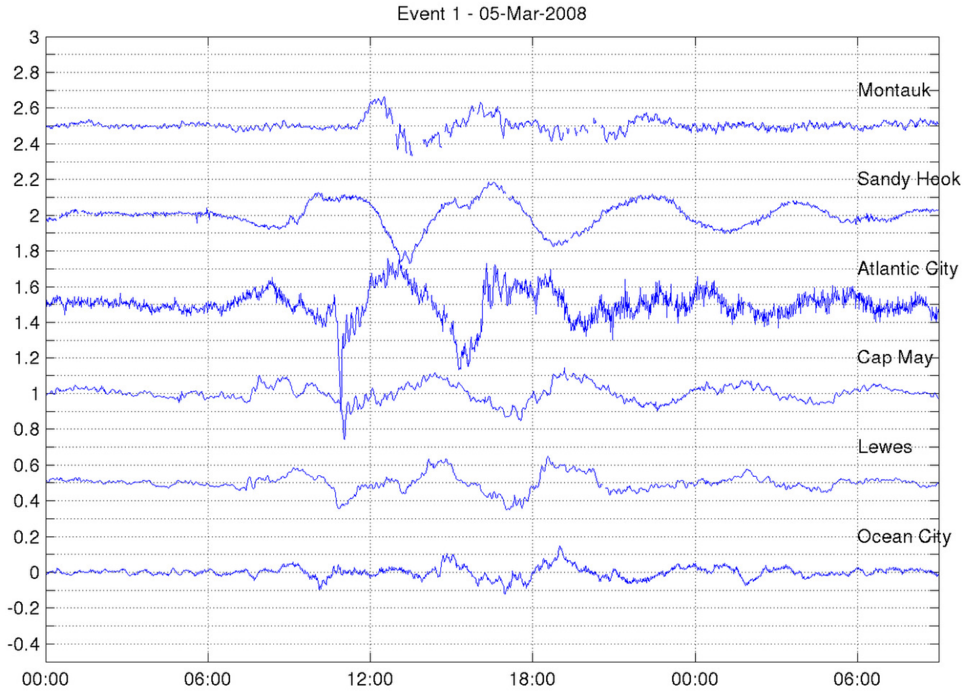


Figure 2. Filtered sea level series collected during event 1.

In addition, a strong sea level drop lasting about 10 min may be found at the beginning of the event, being particularly strong in Atlantic City (60 cm) and Cape May (20 cm), but also detectable at Lewes (10 cm).

To better investigate these oscillations, we performed both spectral and cross-spectral analysis for this event (Figs. 3 and 4). Most of the stations encompass power density spectral peaks around 5 h and 2-2.5 h periods. An increase in energy may be noticed also higher frequencies at some stations (e.g., Atlantic City, Cape May, Lewes), but herein we will focus on periods greater than 2 h. The spectral ratios between high activity periods and calm periods also exhibit peaks at these periods, but the amplitude of these peaks depends of the stations.

Cross-spectra between Atlantic City and Cape May, Lewes and Sandy Hook contain high cross-power spectral density at these periods (~5 h and ~2 h). These peaks are usually associated with high coherence levels (varying between 0.7 and 0.9). For the periods ~ 5 h, there is a phase difference of 90-100° between Atlantic City and Cape May, again 100° between Atlantic City and Lewes (not surprising since Cape May and Lewes are really close to each other) and ~ -120° between Atlantic City and Sandy Hook.

The phase differences between Atlantic City and Sandy Hook and between Atlantic City and Cape May are roughly in agreement with what can be deduced by visual inspection of the series.

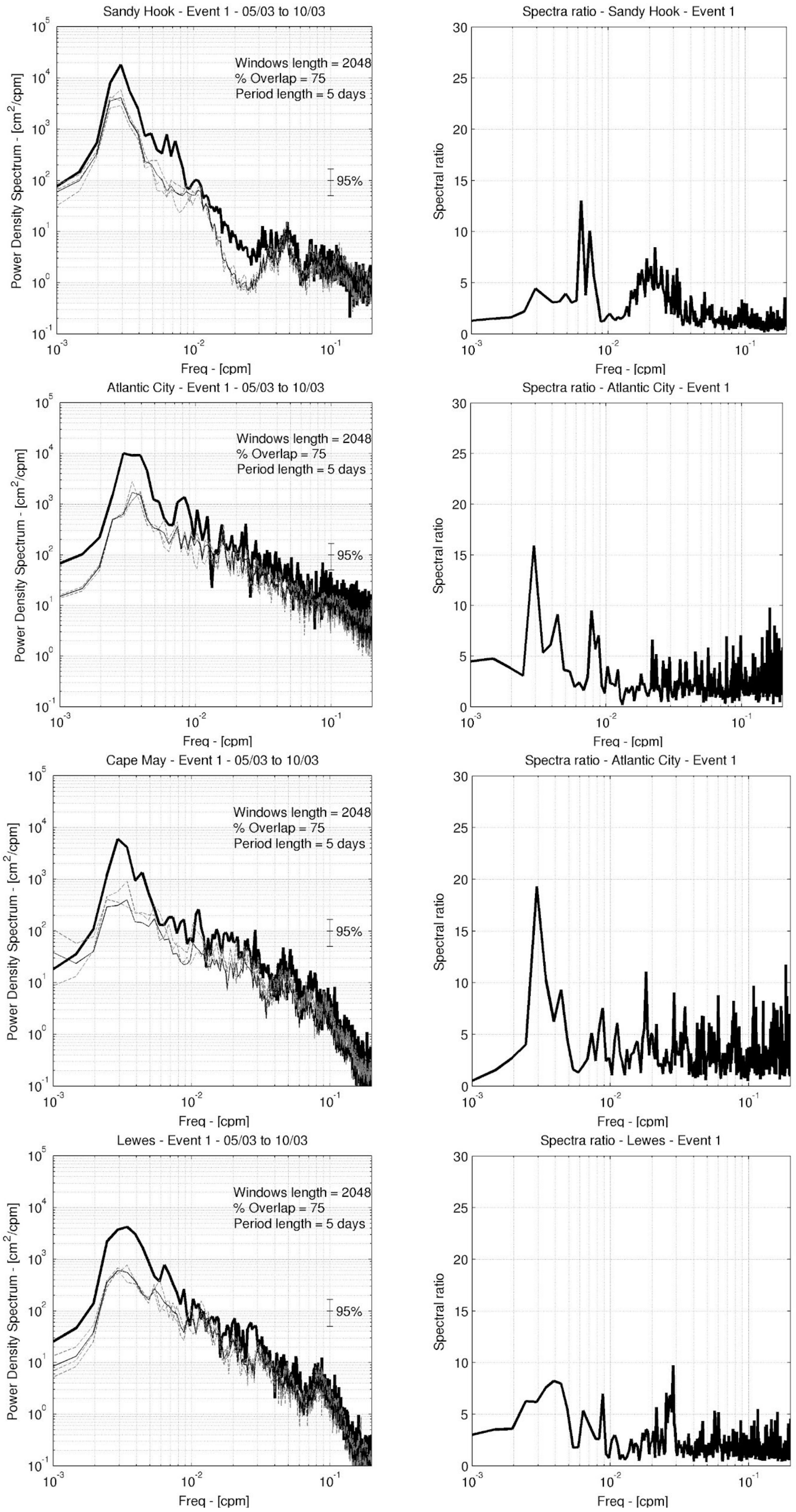
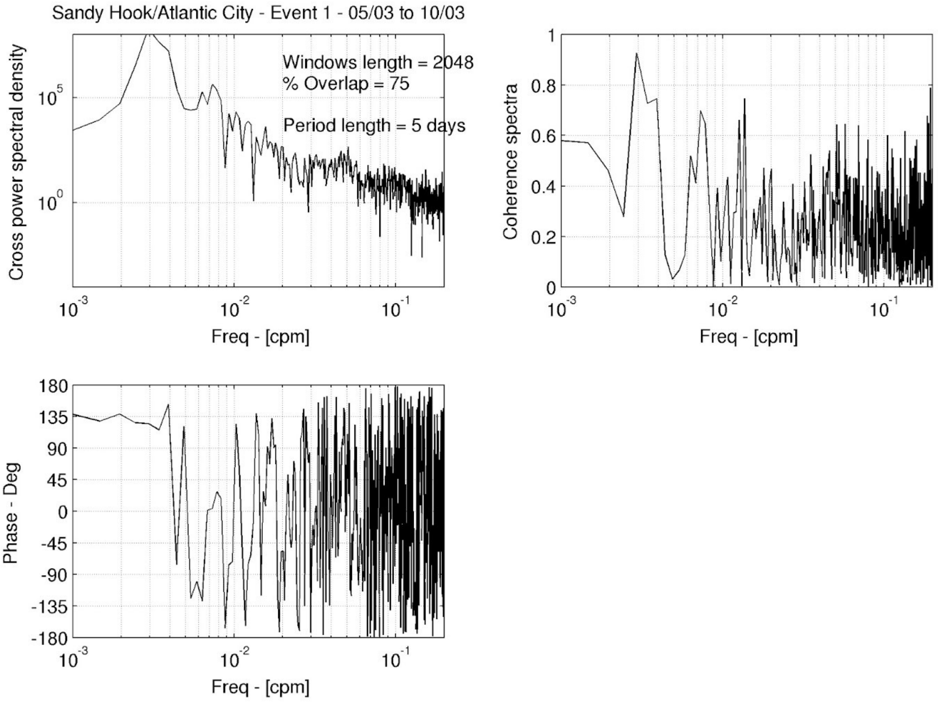
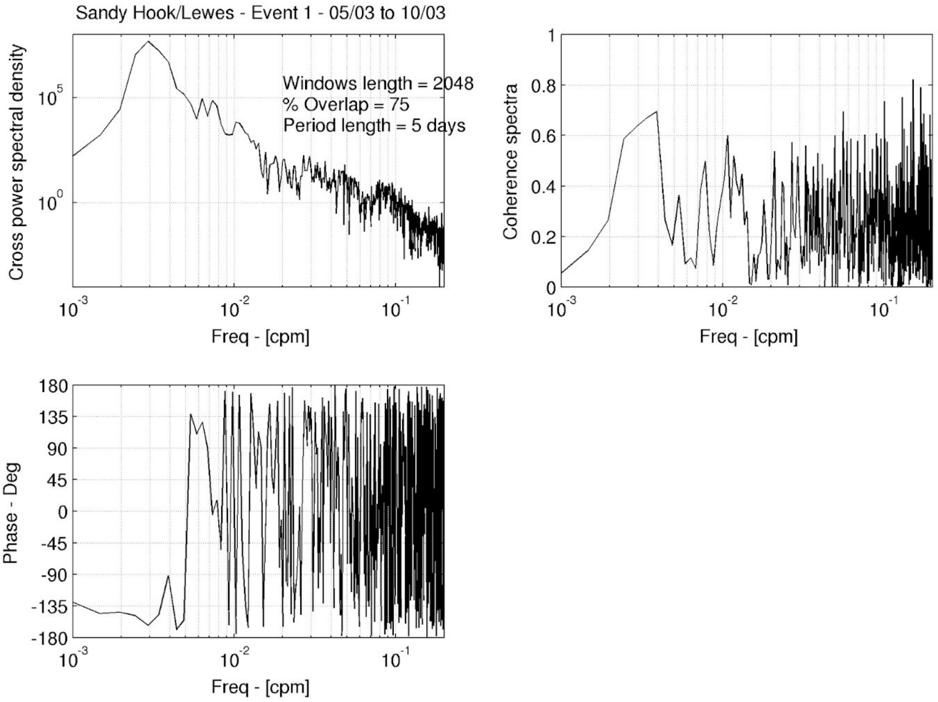


Figure 3. Event (thick) and background (thin) spectra (left) and spectral ratios (right) at different stations during event 1.


Sandy Hook/Atlantic City - Event 1 - 05/03 to 10/03
Windows length = 2048
% Overlap = 75
Period length = 5 days
Cross power spectral density
10^5
10^0
Coherence spectra
1
0.8
0.6
0.4
0.2
0
Phase - Deg
180
135
90
45
0
-45
-90
-135
-180
10^{-3}
10^{-2}
10^{-1}
Freq - [cpm]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Period length = 5 days
Cross power spectral density
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10^0
Coherence spectra
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0.8
0.6
0.4
0.2
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Phase - Deg
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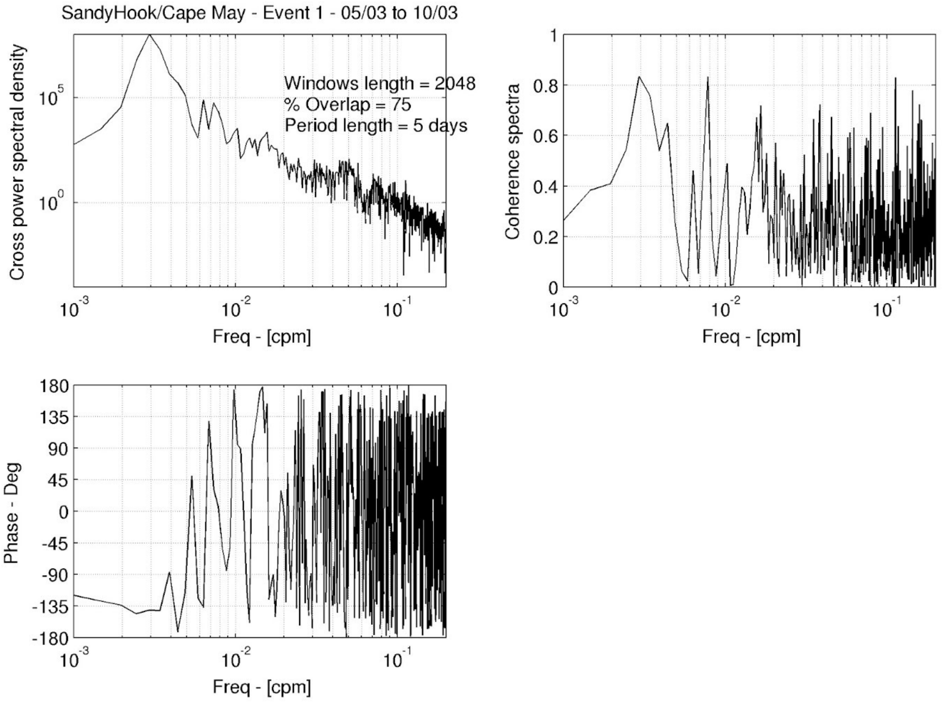


Figure 4. Cross-spectra between different pairs of stations estimated during event 1.

Using the phase information and visual inspection of sea level time series, it seems that these waves propagated southwards along the coast.

Time difference between sea level oscillations at 4.8-5.6 h periods versus alongshore distance taken from the spectra and cross-spectra is plotted in Fig. 5. One can see that time/distance relationship between Sandy Hook, Atlantic City and Cape May are roughly linear, while Lewes is behaving differently, as being separated from other stations by a wide bay. We used the time differences, the distance and oscillation periods to compute the velocity of a wave. The corresponding velocities are reported in the following table:

	T = 5.6 h	T = 4.8 h
Sandy Hook - Cape May	16.3 m/s	19.2 m/s

The velocity can also been determined visually by taking peak-to-peak time differences between each stations. Times series have been band-pass filtered to keep periods between 2 h and 6 h in order to better visualize the low frequency oscillations (Fig. 6).

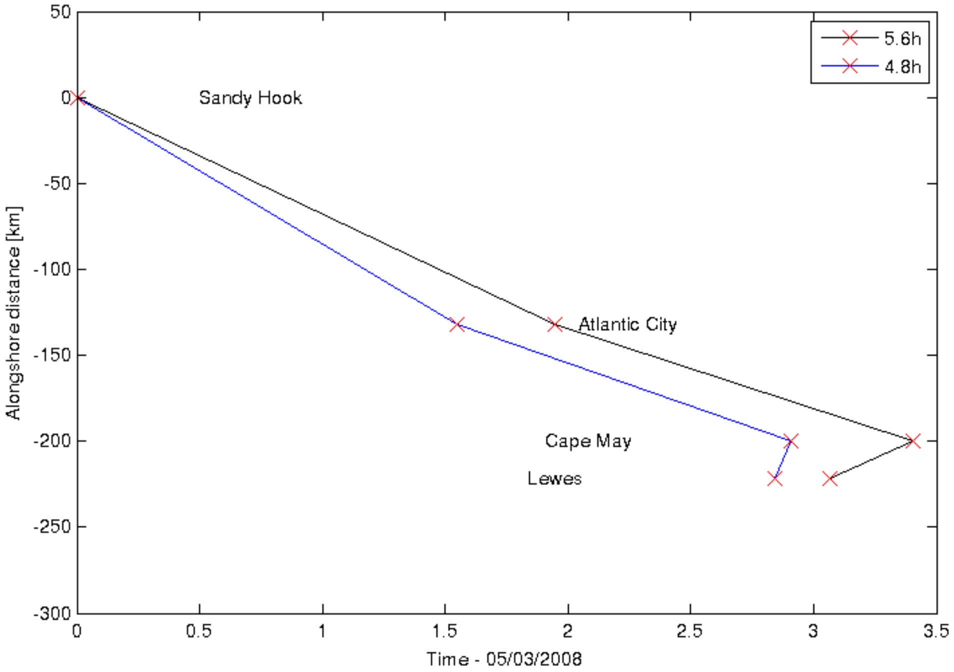


Figure 5. Time difference between sea level peaks versus alongshore distance estimated from spectra and cross-spectra for periods of 5.6 h and 4.8 h during event 1.

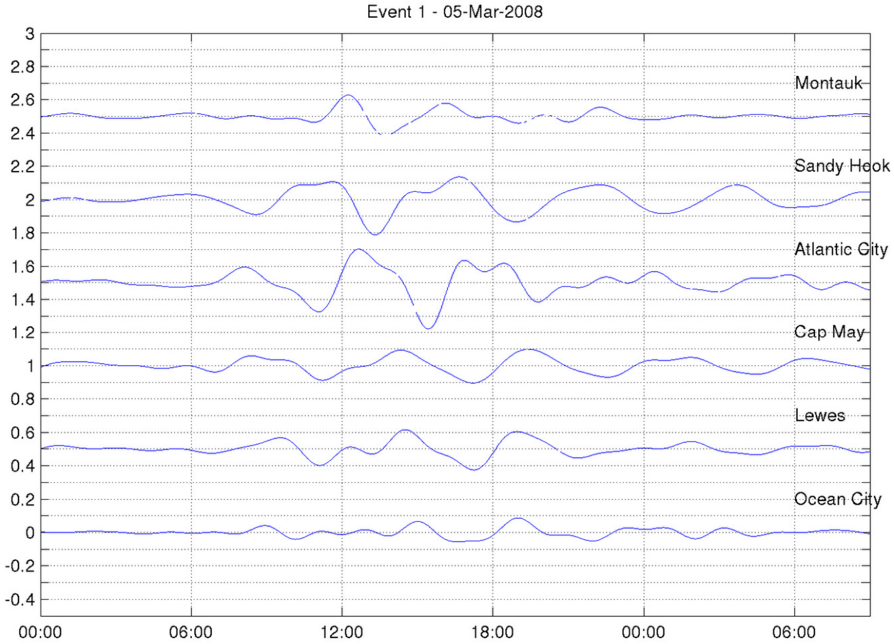


Figure 6. Band-pass filtered sea level series, with cutoff periods at 2 h and 6 h, during event 1.

The relatioship between sea level peaks time difference versus alongshore distance can be seen in Fig. 7. Again, the relationship is linear between Sandy Hook and Cape May, and then increases towards the south. The wave propagation velocity computed from Sandy Hook and Lewes data equals to 18.0 m/s, and from Sandy Hook and Cape May data equals to 16.3 m/s. That is the same range of velocities as determined from spectra and cross-spectra.

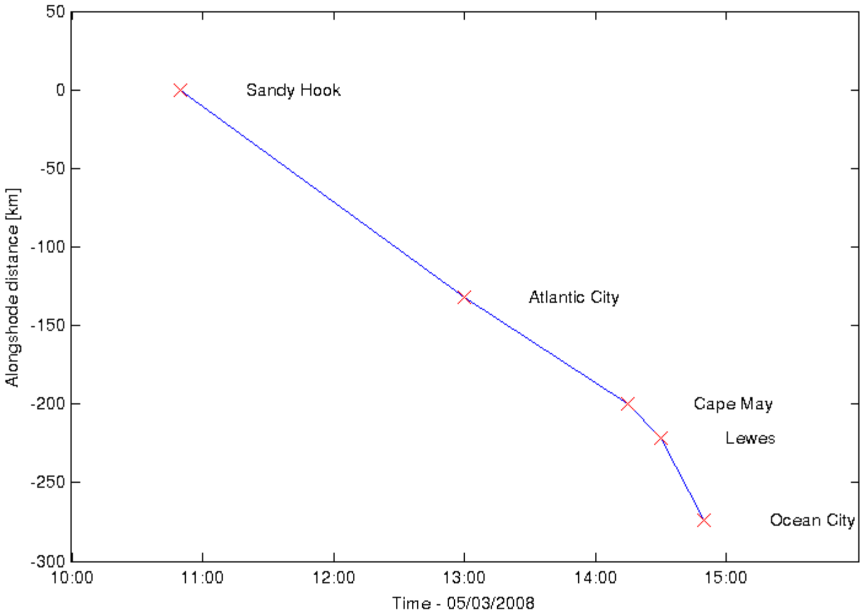


Figure 7. Time difference between sea level peaks versus alongshore distance estimated from filtered series during event 1.

A feasible explanation of such oscillations is that they are edge waves, generated by a cyclone. Similar oscillations (~6 h) generated by a hurricane and propagating along the Florida Coast have been reported and investigated by Yankovsky (2008, 2009). Therefore, we will use an analytical model for propagation of edge waves in our analyses, developed by Ursell (1952) and used by Yankovsky (2008).

An analytical theory has been developed for the edge waves propagating along the shelf of constant slope, which is present in our investigation area (Fig. 8). The model considers the three-dimensional normal modes propagating over a shelf with constant slope α. The dispersion relation is given by (Yankovsky, 2008)

$$\sigma^2 = gk \sin[(2n+1)\alpha]$$

where σ is the wave frequency, g is the acceleration due to gravity, k is the wavenumber and n is the mode number. The slope parameter α equals to 0.0006 rad, being computed from the distance between coastaline and 50 m isobath in the area of Atlantic City, and keeping it constant along the coastline. Considering that $c=\sigma/k$ and α is small, one can compute theoretical velocity of different edge wave modes

$$c = g/\sigma\,(2n+1)\alpha$$

	T = 4.8 h	T = 5.6 h
n = 0	16.2 m/s	18.9 m/s
n = 1	48.5 m/s	56.6 m/s
n = 2	80.9 m/s	94.3 m/s
n = 3	113.2 m/s	132.2 m/s

For the lowest Stokes mode (n=0), which has been normally found to be the most intense one, velocity varies from 16.2 to 18.9 m/s, depending of the frequency considered. This is in good agreement with the observed velocity, considering the approximations and uncertainties of α.

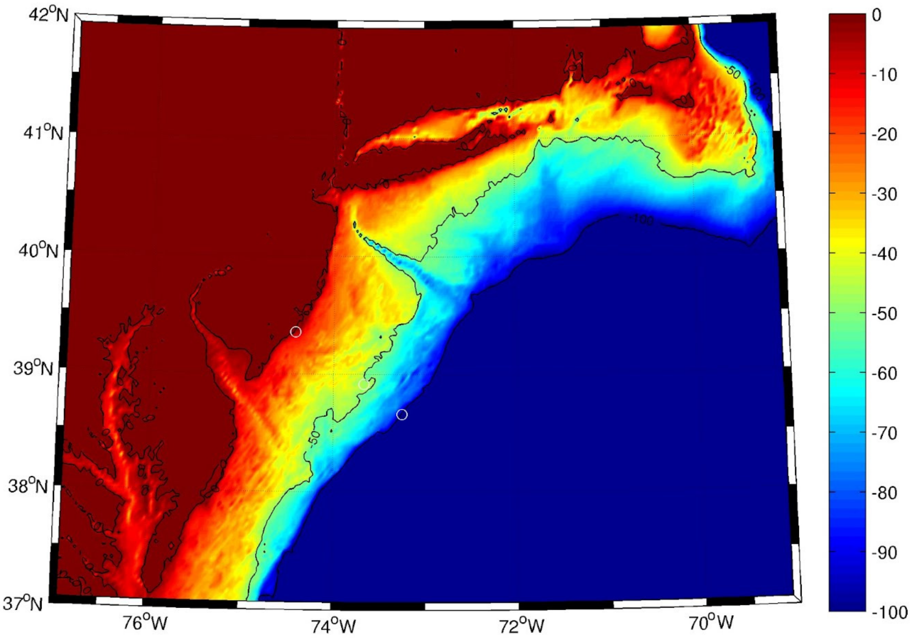


Figure 8. Bathymetry of the area where event 1 occured.

Event 7

Event 7 occurred in the same region and is detected at the same stations as event 1, during the 13 March 2010 (Fig. 9). During this event, we also included Menemsha and Nantucket stations in the analysis. The biggest trough-to-crest values occurred at Atlantic City and reached 95 cm, and at Cape May, where it reached 40 cm. Once again, the oscillations between each station seem to be phase shifted. For instance, Atlantic City and Sandy Hook seems to be out of phase. These waves predominantly consist of low frequency oscillations (~4-5 h) on which higher frequency waves are superimposed, being again the strongest in Atlantic City as during event 1.

As for event 1, we performed spectral and cross-spectral analysis (Figs. 9 and 10). Among Cape May, Lewes and Sandy Hook, the main spectral peaks are at 2.6-2.8 h and also 1.1-1.3 h periods. Atlantic City has a dominant spectral peak at 4.8 and 2.4 h, but its spectral ratio however has dominant peaks at 3.8, 2.8 and 0.9 h.

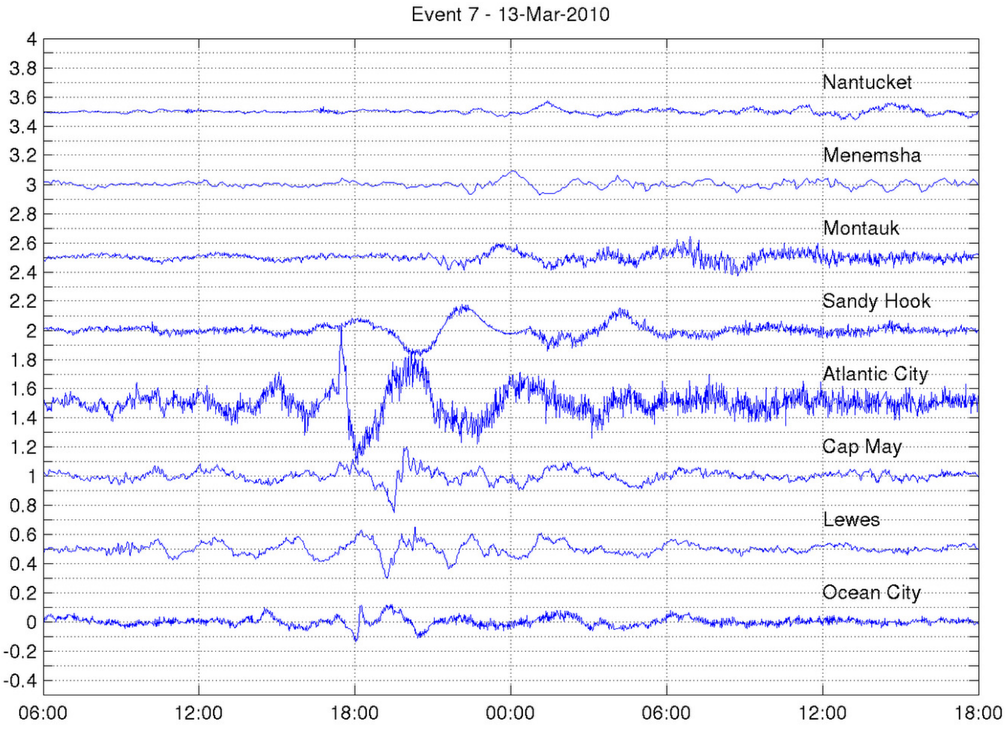


Figure 9. Filtered sea level series collected during event 7.

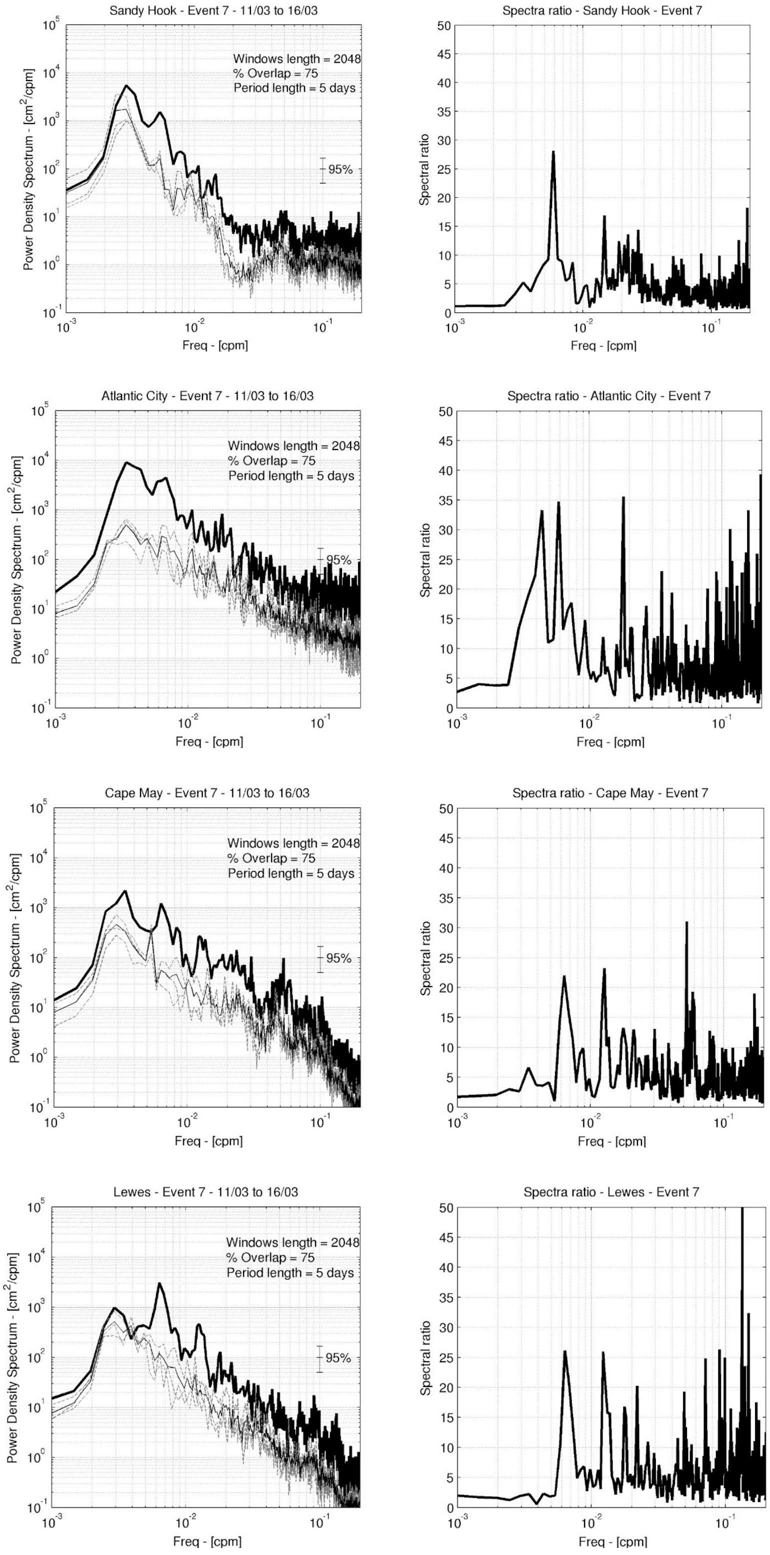
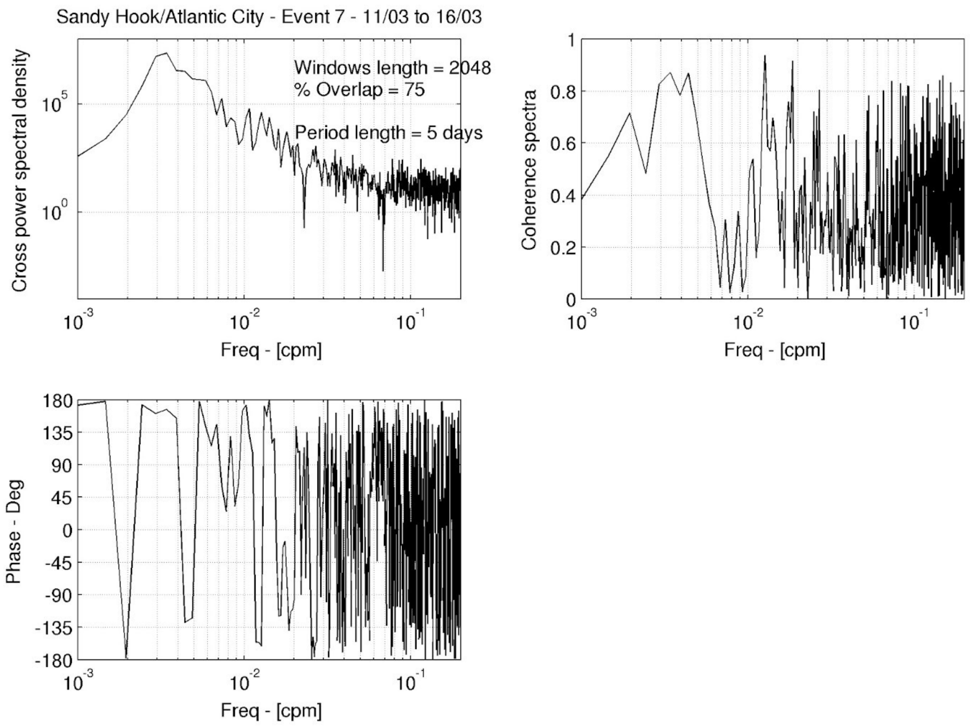


Figure 10. Event (thick) and background (thin) spectra (left) and spectral ratios (right) at different stations during event 7.


Sandy Hook/Atlantic City - Event 7 - 11/03 to 16/03
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% Overlap = 75
Period length = 5 days
Cross power spectral density
10^5
10^0
Coherence spectra
1
0.8
0.6
0.4
0.2
0
Phase - Deg
180
135
90
45
0
-45
-90
-135
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10^{-3}
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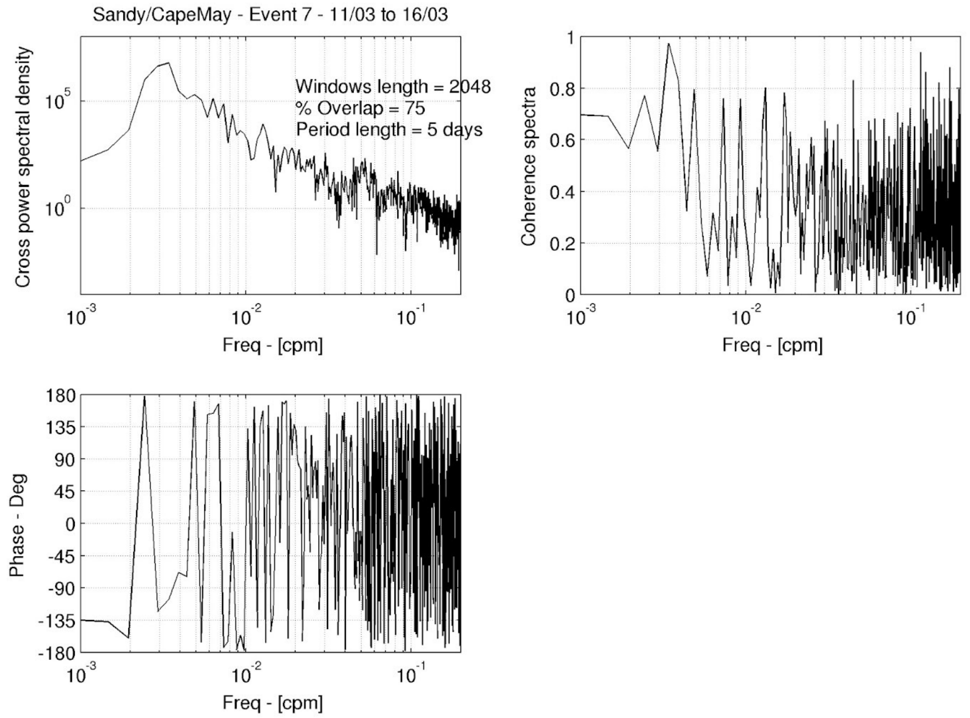
Freq - [cpm]


Sandy/CapeMay - Event 7 - 11/03 to 16/03
Windows length = 2048
% Overlap = 75
Period length = 5 days
Cross power spectral density
10^5
10^0
Coherence spectra
1
0.8
0.6
0.4
0.2
0
Phase - Deg
180
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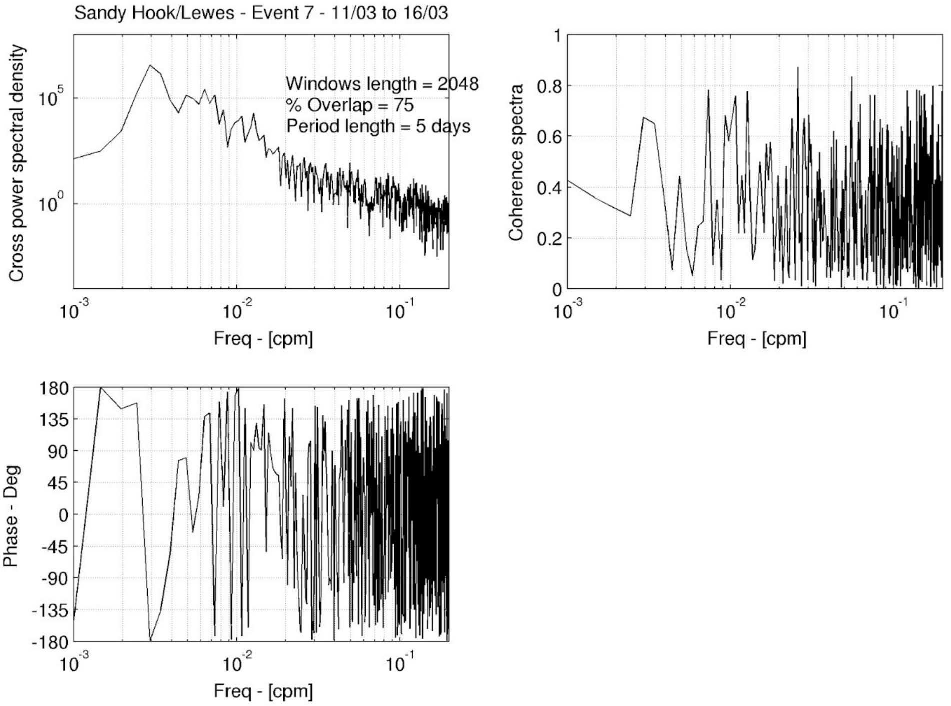

Figure 11. Cross-spectra between different pairs of stations estimated during event 7.

The analysis suggests that 4.8, 2.6-2.8 and 1.3 h are the main periods of the observed oscillations. As for event 1, it seems that these waves are non-stationary waves, presumably edge waves, propagating northward along the coast north of Atlantic City, and southward along the coast south of Atlantic City. This is evidenced when assessing a band pass filtered sea level series with cutoff periods of 2 and 6 h (Fig. 12).

The relatioship between sea level peaks time differences versus alongshore distance can be seen in Fig. 13. Between Sandy Hook and Nantucket, the phase velocity is 29.6 m/s, while between Atlantic City and Sandy Hook 16.3 m/s. The latter velocity is similar to the one observed during event 1, while the wave velocity increased north of Sandy Hook probably to the narrowing of the shelf and increasing of the shelf slope α (Fig. 8)

Also, estimated velocity is much higher than expected between Atlantic City and Cape May (37.7 m/s), presumably indicating a source area for the observed edge waves lying somewhere between these two stations. Therefore, this velocity is unrealistic and should not be taken into consideration.

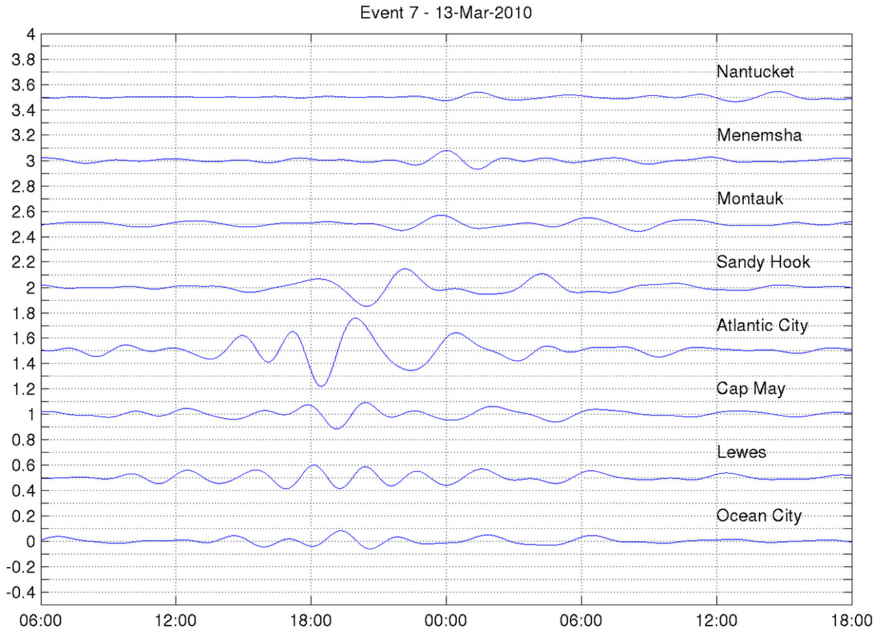

Figure 12. Band-pass filtered sea level series, with cutoff periods at 2 h and 6 h, during event 7.

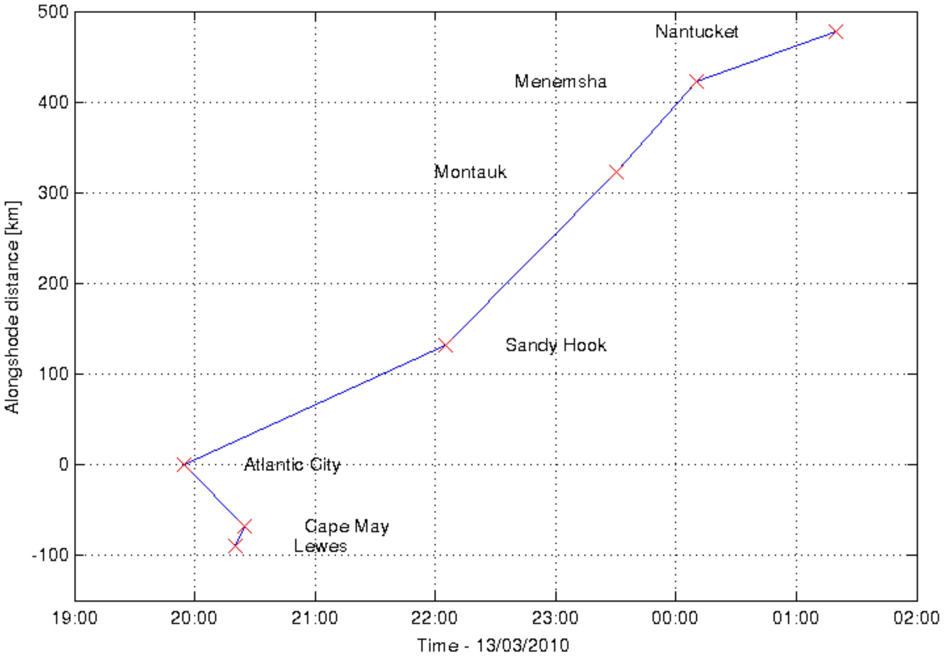

Figure 13. Time difference between sea level peaks versus alongshore distance estimated from filtered series during event 1.

The theory used in assessment of the event 1 waves is valid also for the event 7 waves. Accordingly, the lowest Stokes mode of edge waves has the following velocities over a shelf slope with constant slope angle α of 0.0006 rad:

	T = 4.8 h	T = 2.8 h	T = 2.6 h	T = 1.3 h
n=0	16.2 m/s	9.6 m/s	8.9 m/s	4.4 m/s
n=1	48.5 m/s	28.7 m/s	26.6 m/s	13.2 m/s
n=2	80.9 m/s	47.8 m/s	44.3 m/s	22.1 m/s
n=3	113.2 m/s	67.0 m/s	62.0 m/s	30.9 m/s

We may note that, for a given mode, velocity decreases whith the period and increases with the order of a mode. For the 0th (Stokes) mode, velocities range from 4.4 m/s to 18.9 m/s, depending on the chosen wave period.

As for the event 1, real velocities have been computed using phase shift information derived from cross-spectral analysis for the periods with significant energies. However, the computed phase shift do not have the information about the number of waves lying between two neighbouring stations, and pure estimation of phase shift will result in unrealistic overestimation of wave velocities.

Therefore, we applied narrow band-pass filters to extract the waves at specific periods, and to compute number of waves lying between stations. For example, the time shift between Sandy Hook and Atlantic City maximum waves having periods between 2 and 3 h indicate that approximately 1.5 waves can be placed betweeen these stations (Fig. 14). Therefore, 360^{o} should be added on phase difference estimated from cross-spectra for waves at 2.6 and 2.8 periods.

Finally, velocities estimated from the phase shift spectra and band pass filtering can be summarized as:

	T = 5.6 h	T = 4.8 h	T = 2.8 h	T = 2.6 h	T = 1.3 h
SandyHook/Atlantic City phase shift	-199^{o}	-194^{o}	-577^{o}	-604^{o}	-2321^{o}
SandyHook/Atlantic City velocity	11.8 m/s	14.2 m/s	8.1 m/s	8.3 m/s	4.3 m/s
Theoretical Stokes mode (n=0)	18.9 m/s	16.2 m/s	9.6 m/s	8.9 m/s	4.4 m/s

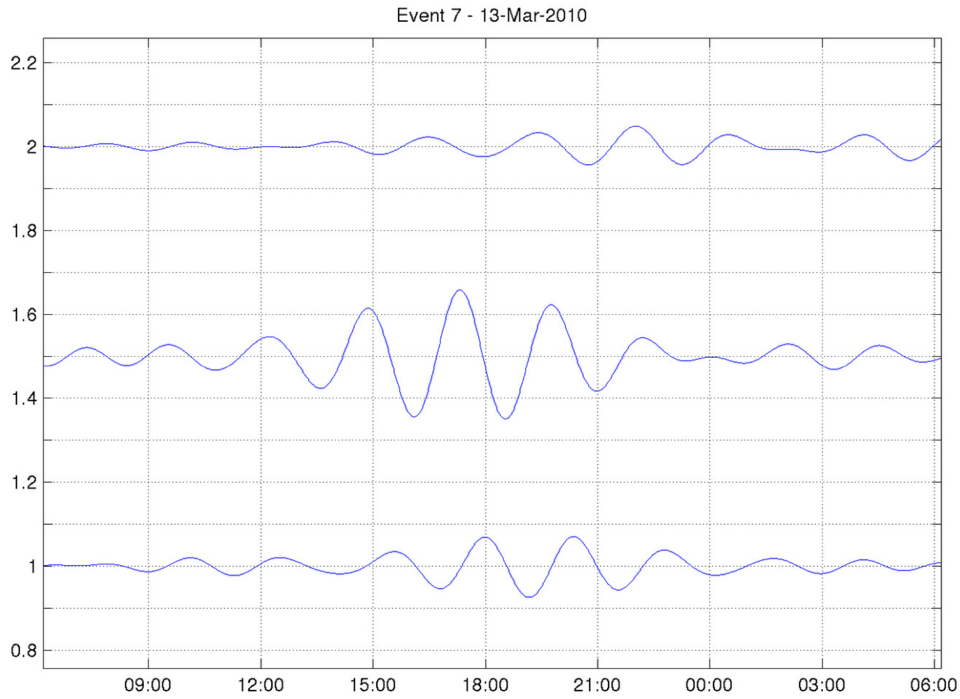

Fig. 14. Temporal evolution of the sea level at Sandy Hook (top), Atlantic City (middle) and Cape May (bottom), over periods between 2 and 3 h.

Event 6:

Event 6 occured during 26 February 2010 and has been detected at following stations: Bar Harbor, Portland, Wells, Fort Point, Boston and Menemsha (Fig. 15). Maximum trough-to-crest height of the wave reached 95 cm in Boston, 40 cm in Portland and 38 cm in Fort Point.

The pattern seems to be similar for all stations (Fig. 16). A slight increase of the sea level occurs during last hours on 25 February, and the sea level decreases significantly few hours later. Then the biggest wave appeared, followed by several other oscillations, whose amplitude decayed in time. The number of oscillations depends of the station: there are several of them in Portland (>10) and just one in Forth Point. The highest wave amplitude occurs at the same time for all stations, between 4 and 5 am on 26 February.

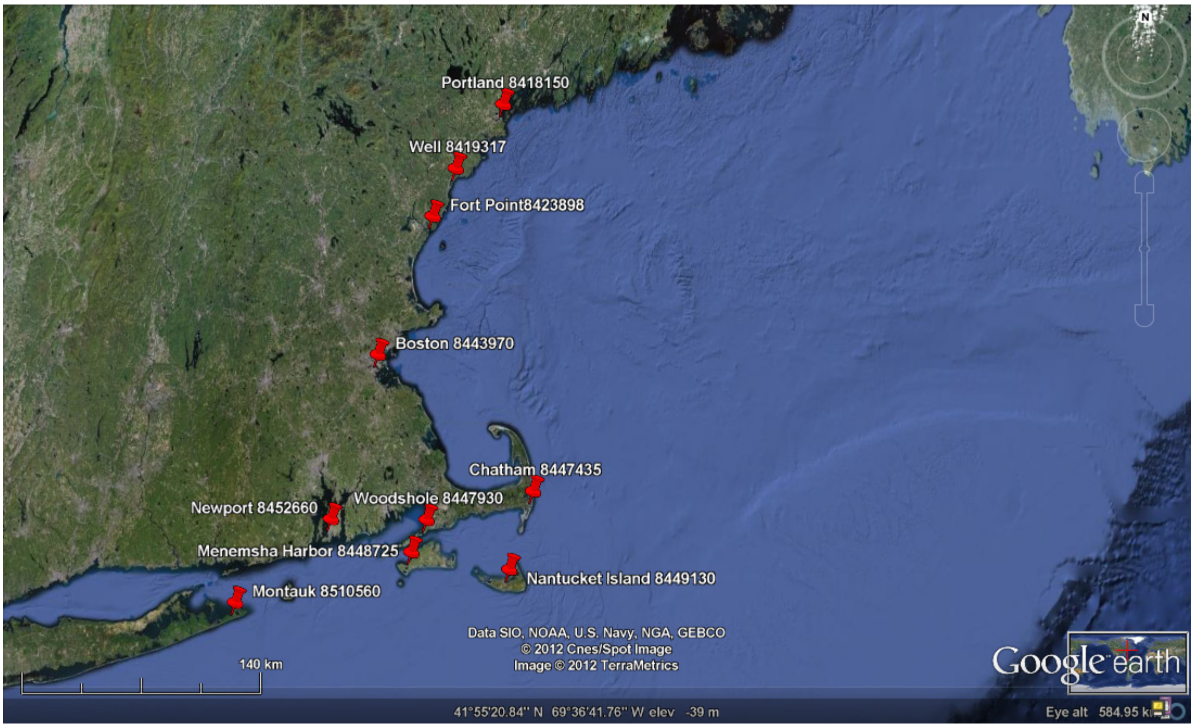

Figure 15. Location of tide gauge stations used for analysis of event 6.

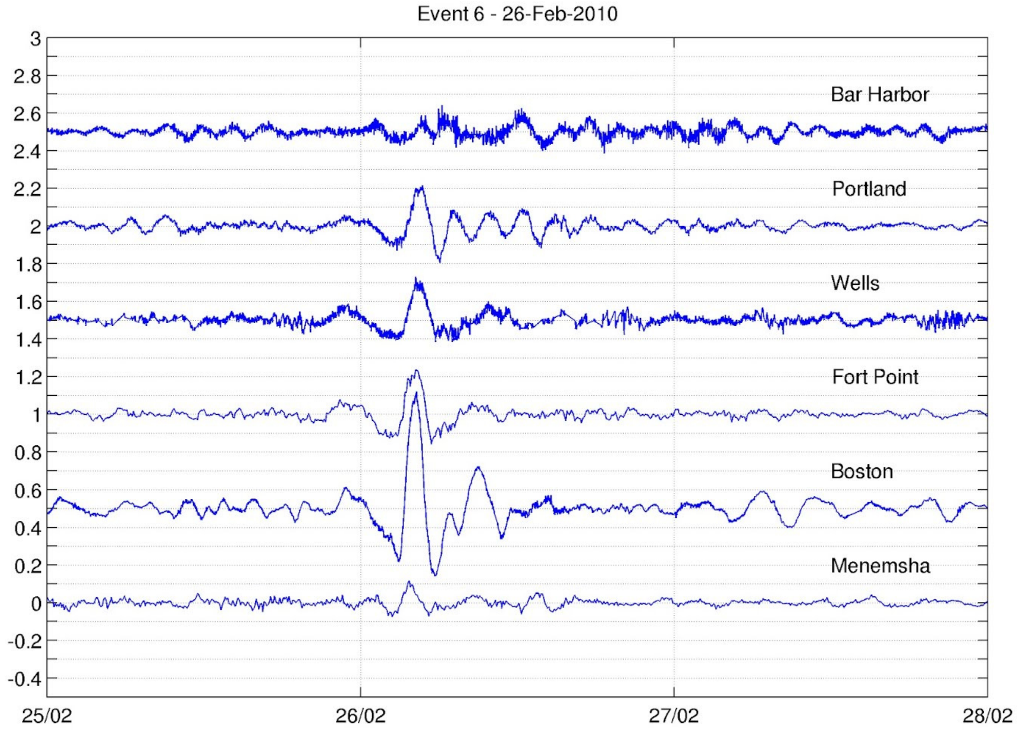

Figure 16. Filtered sea level series collected during event 6.

Spectral analysis (Fig. 17) found the highest event-to-background spectral ratios in Boston, Portland and Fort Point. There is a high degree of similarity between spectral ratios at Fort Point and Boston, both having sharp peaks at 4.8-5.6 h and 2.6-2.8 h. Spectral ratio in Wells has a similar shape but is weaker, probably due to position of the tide gauge that is placed inside a lagoon. At Portland, two peaks may be found at 2.0 and 2.6 h, and a broader one over periods greater than 4 h. At the most south and most north stations, Bar Harbor and Menemsha, there are no strong spectral peaks at specific frequencies, indicating that the event did not occur significantly at these two stations.

Cross spectral analysis (Fig. 18) indicate that the oscillations at these frequencies possess a high level of coherence between some stations. Boston and Fort Point are roughly in phase at 2.6/2.8 h and 4.8 h, and have a high level of coherence. The coherence at 4.8 h period is high also between Portland and Boston/Fort Point, slightly differing in a phase (~20 deg). Therefore, it seems that the 4.8 h oscillations may be attributed to a fundamental mode of standing waves generated over the shelf, encompassing the region from Cape Cod Bay to north of Portland, while 2.6/2.8 h oscillation is probably the first mode. Finally, the 2 h oscillations observed at Portland

and not observed at Fort Point and Boston are possibly related to some standing oscillations occurring in a complex Portland area bathymetry.

A proof for the observed stationary nature of these sea level oscillations, and their spatial outreach, should be provided by a numerical model excercises.

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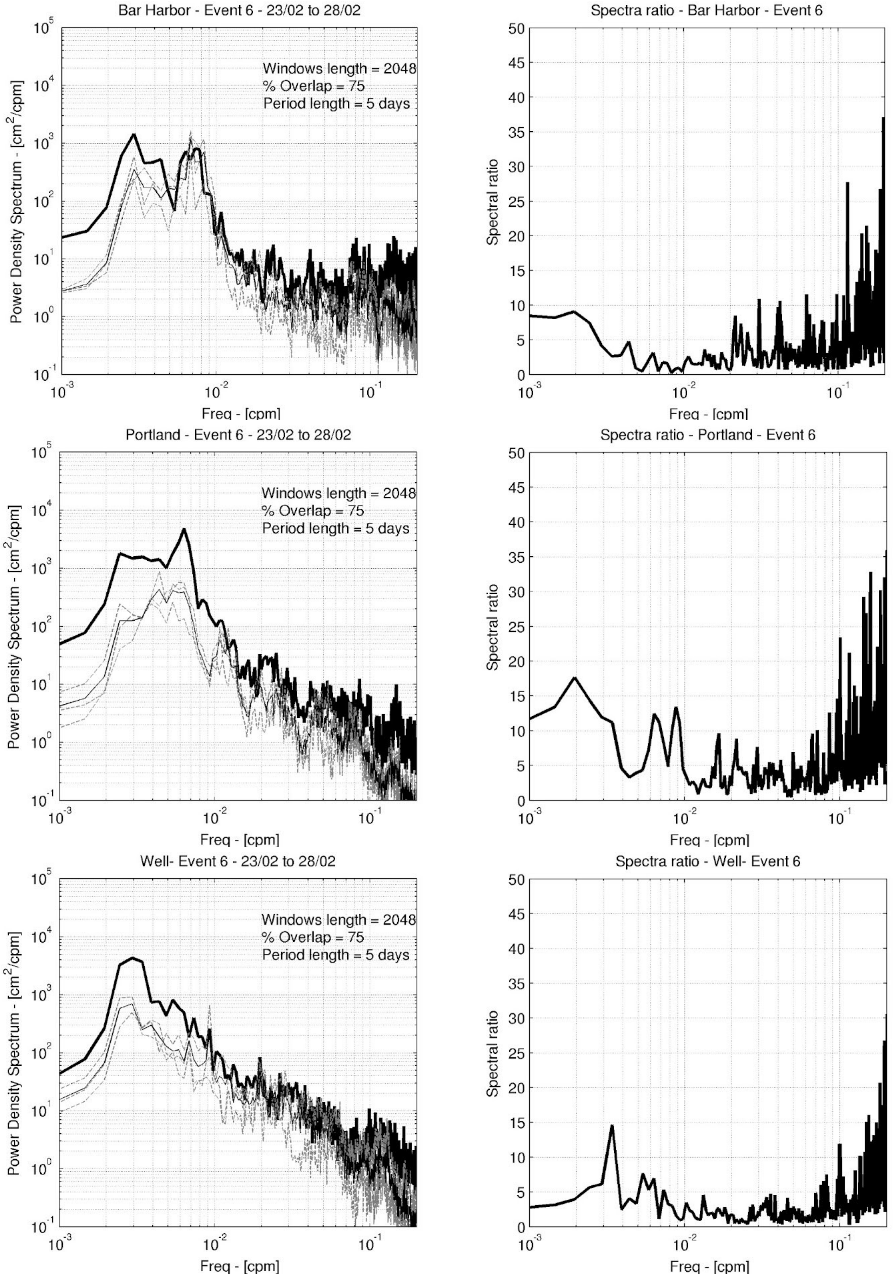


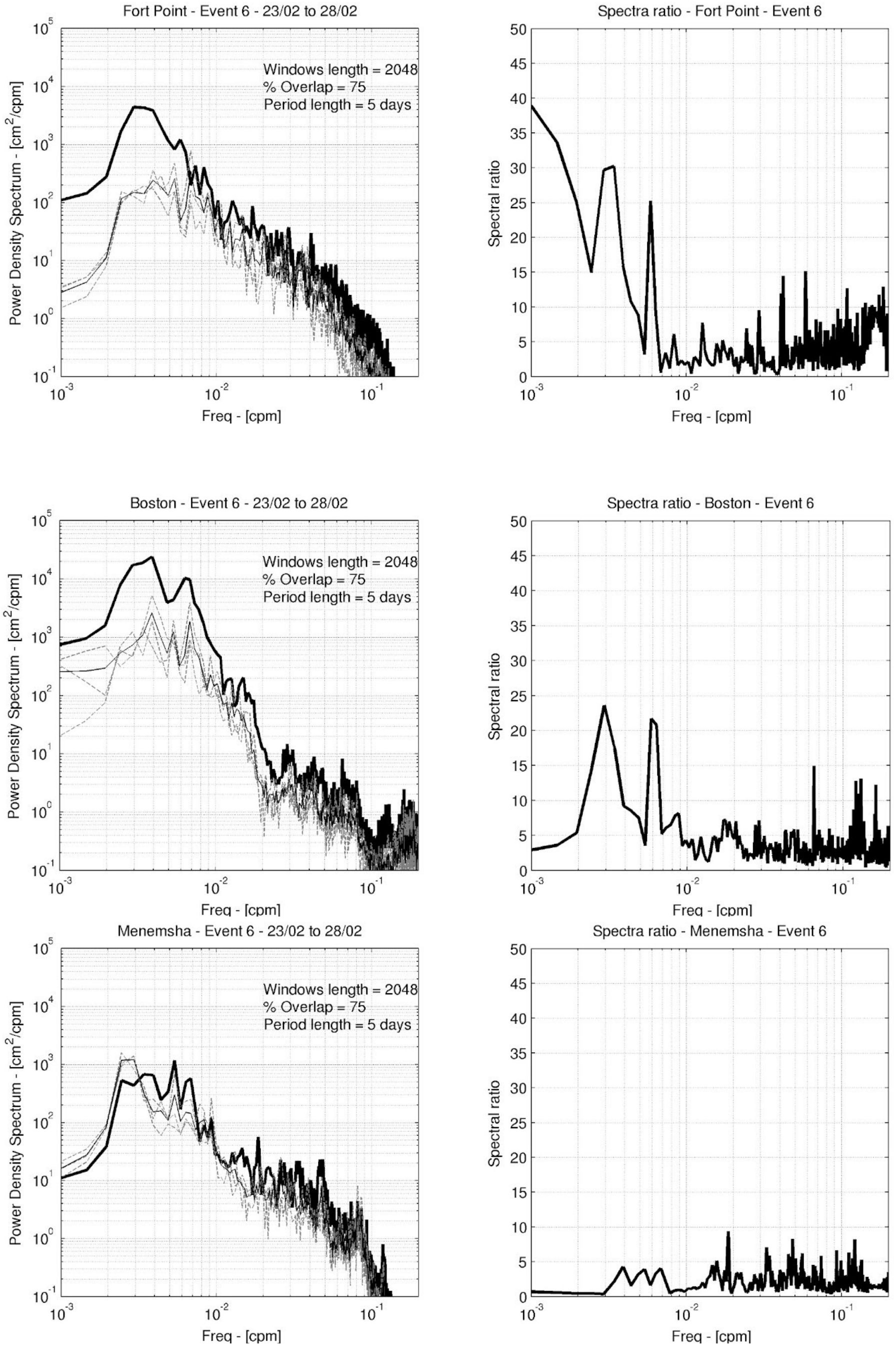
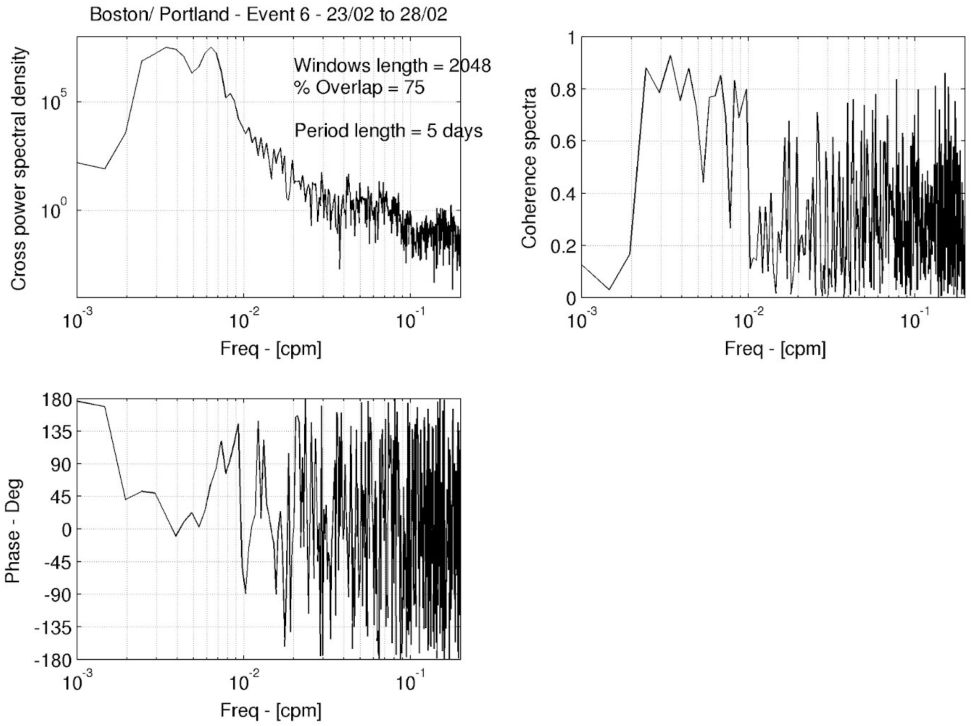


Figure 17. Event (thick) and background (thin) spectra (left) and spectral ratios (right) at different stations during event 6.

	2h	2.4h	2.6h	2.8h	4.8h
Coherence					
Boston/Portland		0.85	0.77		0.93
Boston/Fort Point	0.92		0.88	0.91	0.95
Portland/Fort Point	0.83			0.85	0.96
Phase-shift (°)					
Boston/Portland		83	62		18
Boston/Fort Point	-24		-6	-5	-4
Portland/Fort Point	-118			-25	-23



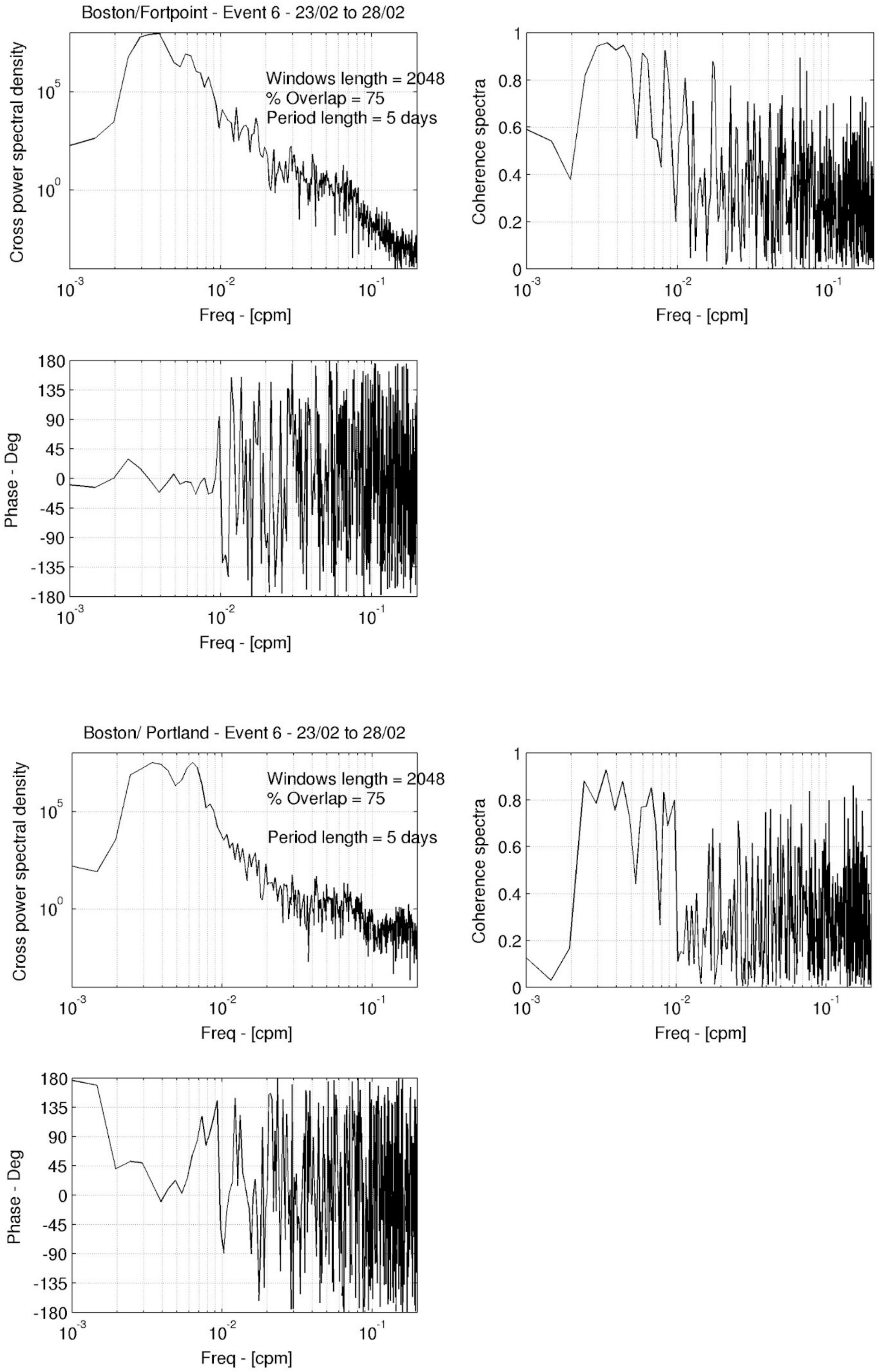


Figure 18. Cross-spectra between different pairs of stations estimated during event 6.

Conclusions

We investigated three of nine potential meteotsunami events happened along the U.S. coastline between 2005 and 2011, by analysing high-resolution sea level data measured at a number of stations. The following conclusions may be written:

- Events with both non-stationary nature of sea level oscillations (edge waves) and standing oscillations have been reported, being a contributor for the observed strong sea level oscillations. Stationary and non-stationary waves have been reported in different basins.

- The nature of sea level oscillations on an hourly timescale (from 1 to 6 h) has been investigated, as these oscillations were detected at a number of stations. However, some strong oscillations over a minute timescale were observed as well (e.g., at the Atlantic City tide gauge during events 1 and 7), which demand more carefully investigations. This may be done by choosing shorter cutoff period for filtering (e.g., 1 h), and by focusing on the strongest sea level oscillations observed on subhourly timescale.

- This report does not include any assessment of the generating force of the observed waves, which should be investigated through analysis of meteorological observations and atmospheric reanalysis fields.

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