Report on synoptic and satellite product data analysis of the 28 October 2008 Boothbay meteotsunami event

On 28 October 2008 around 3 pm (19 UTC) significant sea-level oscillations were reported in Boothbay Harbor, Southport and Bristol (Maine). According to eyewitnesses reports the sea-level in the harbor rose by more than 3.5 m in 15 minutes and then recessed, followed by several more waves of similar amplitudes and periods. The first wave hit the harbor shortly before 15 (3 pm) local time (18 UTC) and the oscillations lasted until about 19 UTC with app. 20 minutes period, according to reports and some available still images. Since the event is considered to be of atmospheric origin, the analysis of the state of the atmosphere preceding the event will be presented here.

Mean sea-level pressure charts suggest that the region of Boothbay was under the influence of an intense low pressure system with two centers (1010 hPa) seen in the image for 00 UTC (Figure 1) (color shades). In the upper levels (500 hPa, shown here as black lines) the region was under the influence of strong south-westerly upper-level flow on the leading side of a deep upper-level trough.

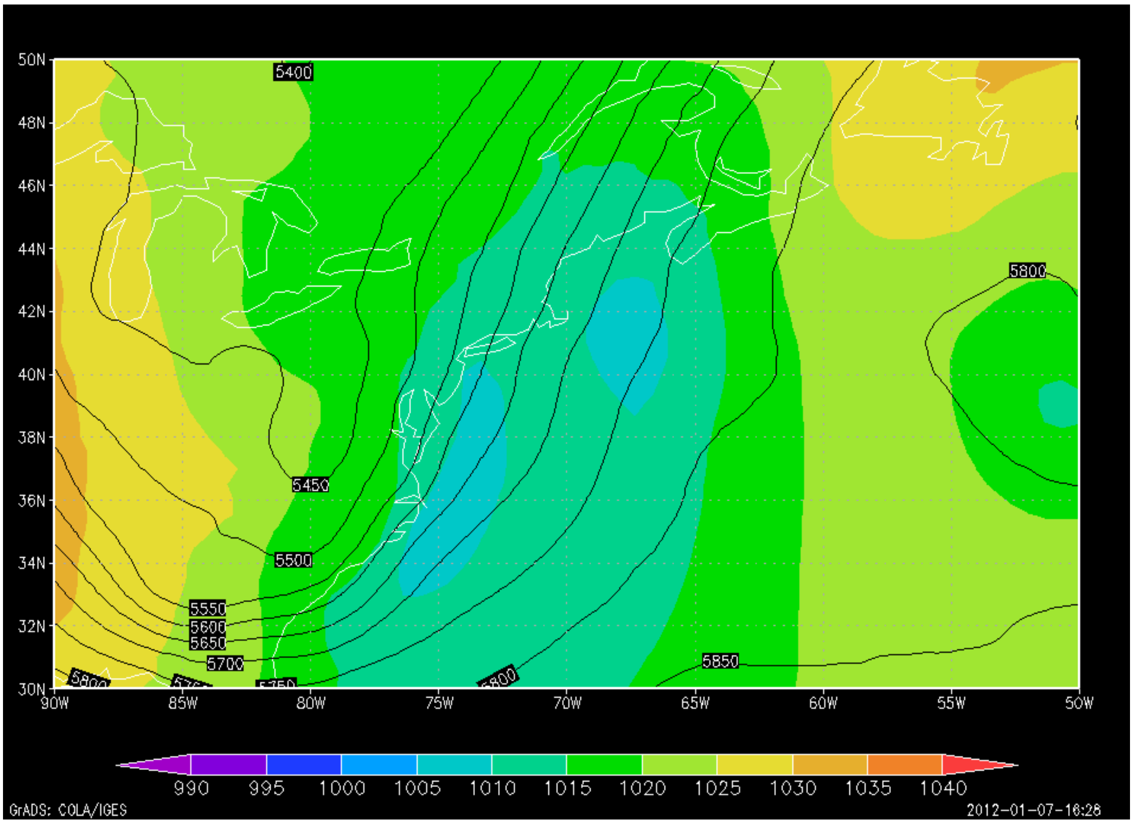


Figure 1: MERRA reanalysis data for 28 Oct 2008, 00 UTC. Color shades: mean sea-level pressure; black lines: 500 hPa height

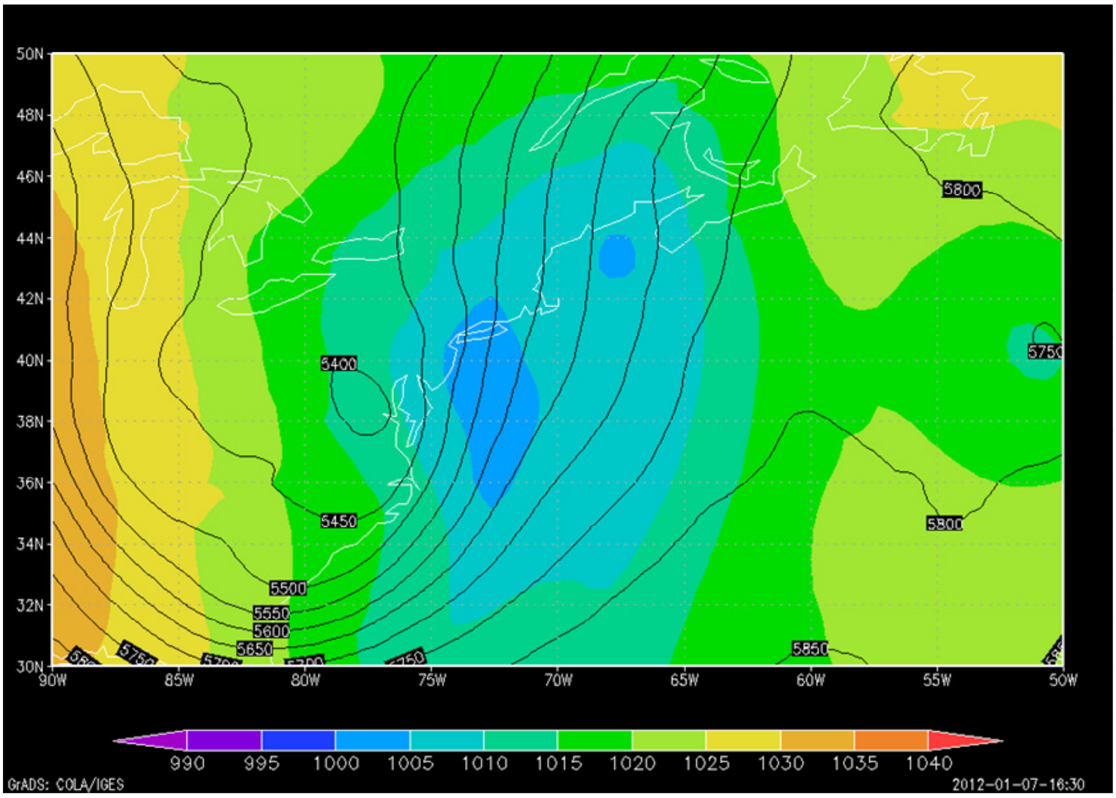


Figure 2: MERRA reanalysis data for 28 Oct 2008, 06 UTC. Color shades: mean sea-level pressure; black lines: 500 hPa height

In the next 6 hours the surface low is deepening. The pressure in the centers at 06 UTC is below 1005 hPa (Figure 2). The upper-level trough is also deepening and an upper-level low centre appears in the 06 UTC image. The gradient of the 500 hPa height isolines suggests very strong upper-level southerly wind.

6 hours later both surface and upper-level lows show that a very intense cyclogenesis is taking place (Figure 3). In the surface pressure centre the pressure is now below 995 hPa, meaning that the pressure dropped for app. 10 hPa in 6 hours. While the surface low remained quasi-stationary, the upper-level low has moved eastwards, catching up with the surface center, and deepened.

At 18 UTC (Figure 4) surface pressure has dropped under 990 hPa. The tilt between the surface low and the 500 hPa low is now smaller, the low axes being quasi-vertical. The gradient of 500 hPa height isolines suggests that the upper-lever wind speed increased, now having southerly direction over the sea, but south-easterly at the coast, with speed over the coast exceeding 45 m/s (image not shown here).

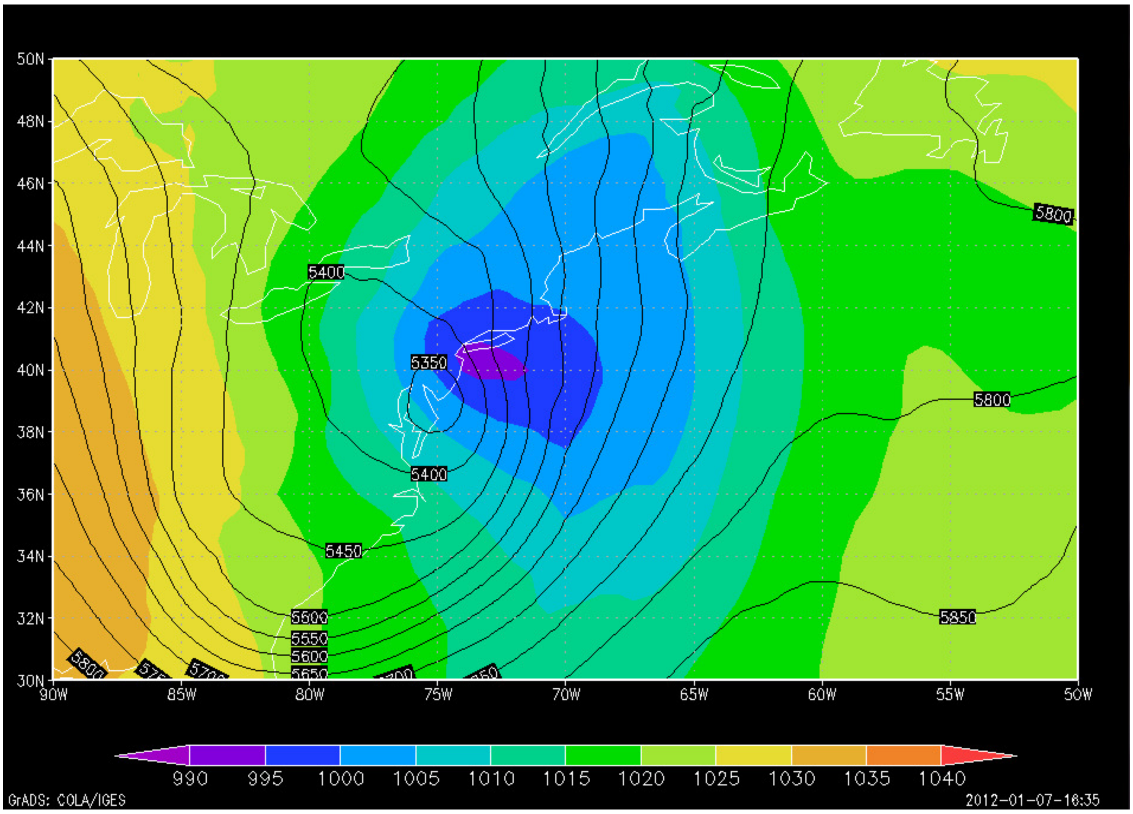


Figure 3: MERRA reanalysis data for 28 Oct 2008, 12 UTC. Color shades: mean sea-level pressure; black lines: 500 hPa height

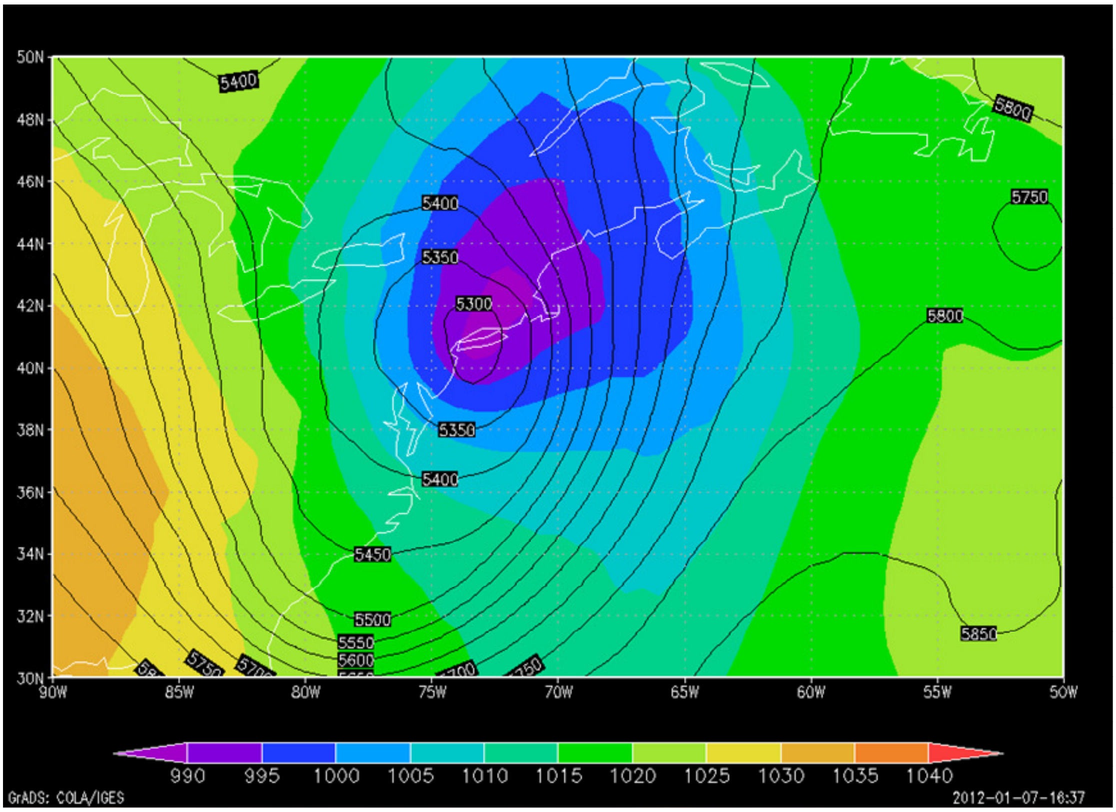


Figure 4: MERRA reanalysis data for 28 Oct 2008, 18 UTC. Color shades: mean sea-level pressure; black lines: 500 hPa height

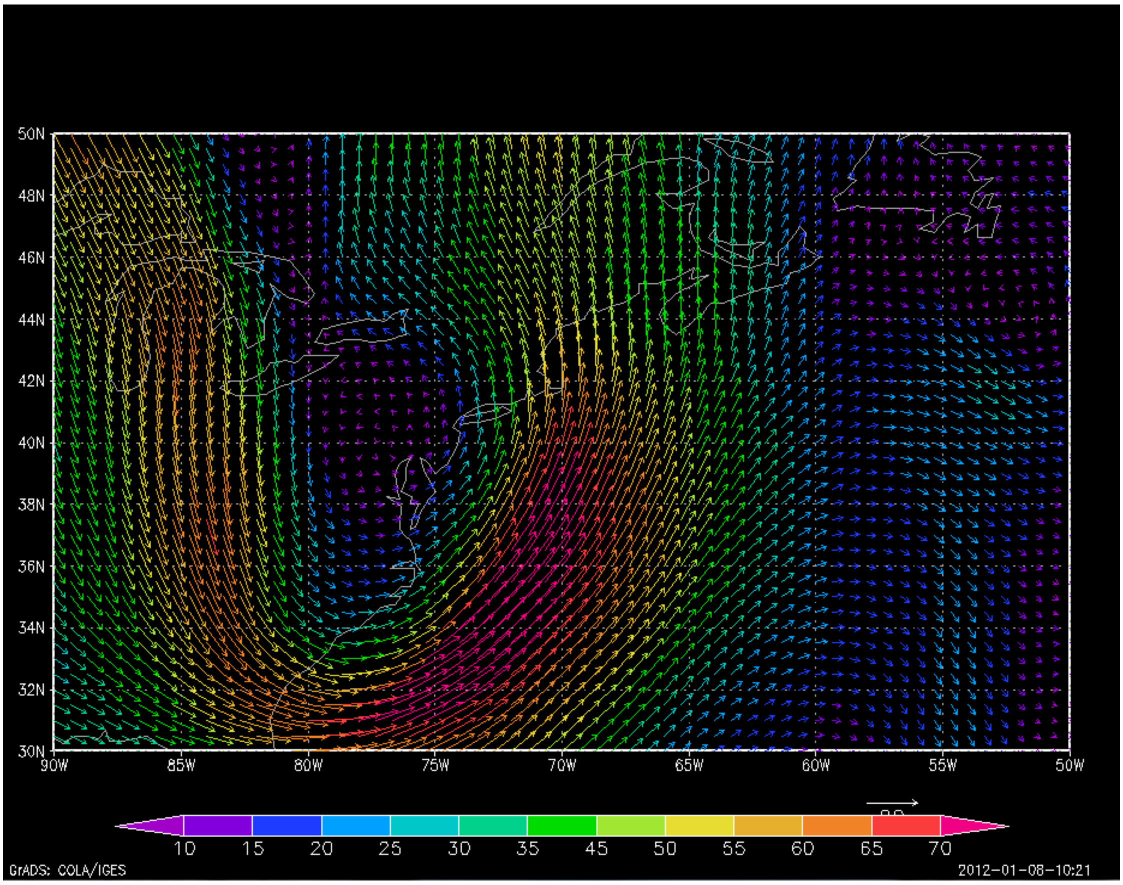
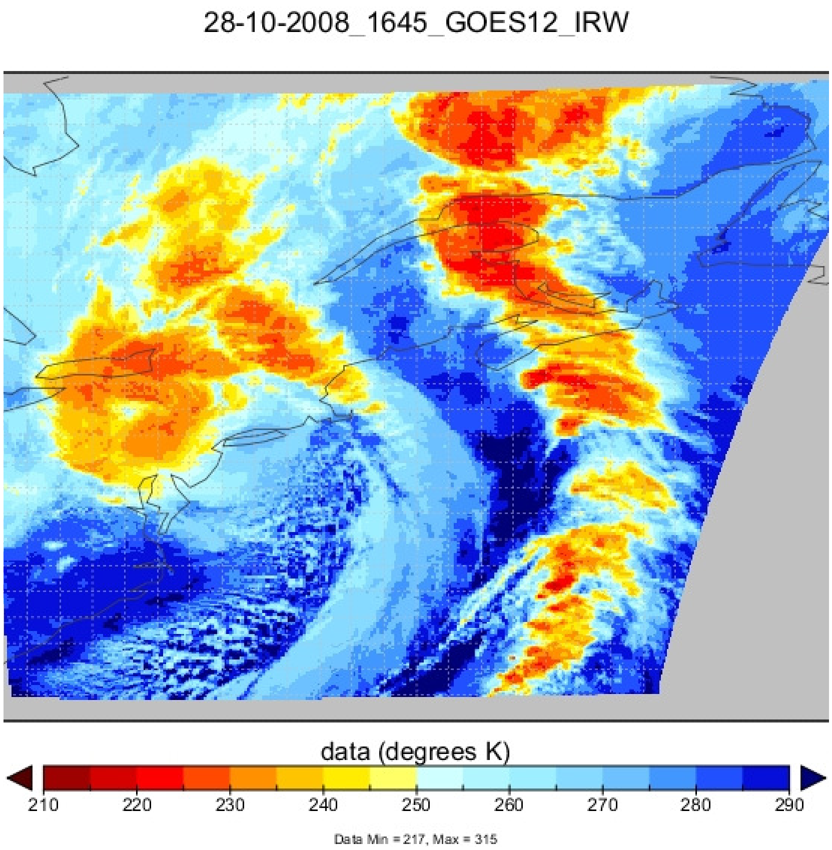


Figure 5: MERRA reanalysis data for 28 Oct 2008, 18 UTC. Color arrows: 300 hPa wind

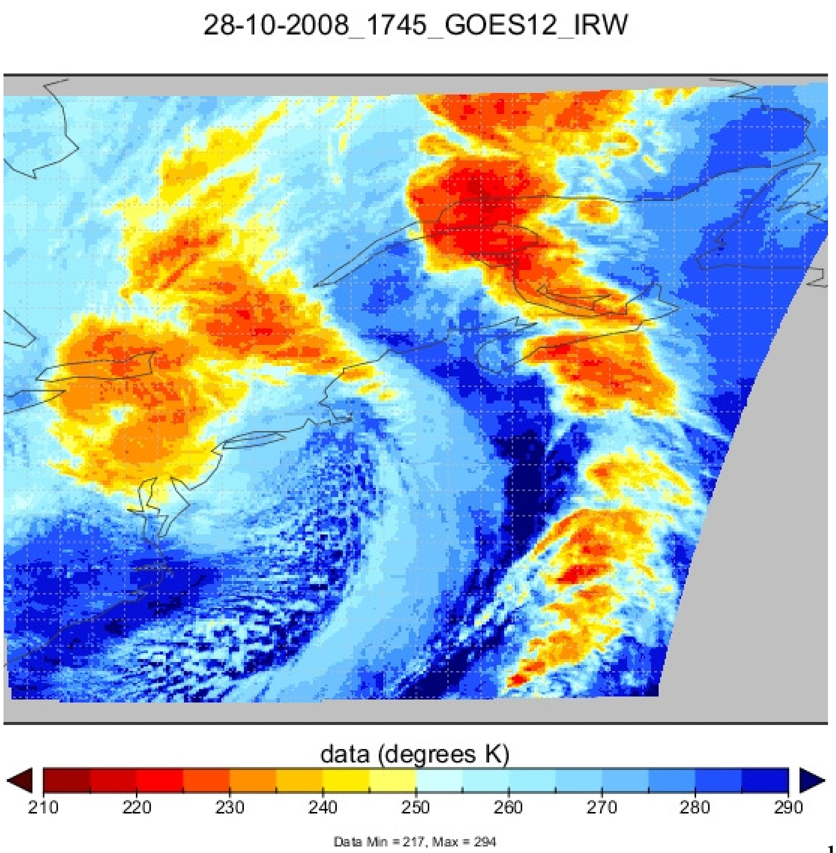
300 hPa wind field (Figure 5) shows a very pronounced south-westerly jet with wind speed in the jet-streak exceeding 70 m/s.

Analysis of satellite and radar data

Satellite data on 28 October 2008 reveal two frontal systems, one situated east of the region of Boothbay (this will be further analyzed in the Discussion) and one, connected to previously mentioned low pressure center, approaching the region of interest (Figs. 6 a-d). The difference between the two systems is twofold: the front on the east has much colder (higher) clouds within the frontal cloud band whereas the clouds in the frontal system approaching Boothbay are mostly medium and low level clouds, and second: it seems that the speed of movement of two fronts is different (the western front is catching up with the eastern one, therefore moving faster). Also, the first front had a more westerly component of velocity, with clouds moving northeastwards. Out of the frontal system related to a cyclone, special attention must be paid to the cold front. It can be concluded from the sequence of satellite data that the clouds of the cold front were moving from south to north and in the later stage (which is in agreement with upper-level wind field from previous chapter), while passing over Boothbay, cloud movement was from southeast to northwest (see satellite images around 19 UTC, Figs. 6c and 6d).



a



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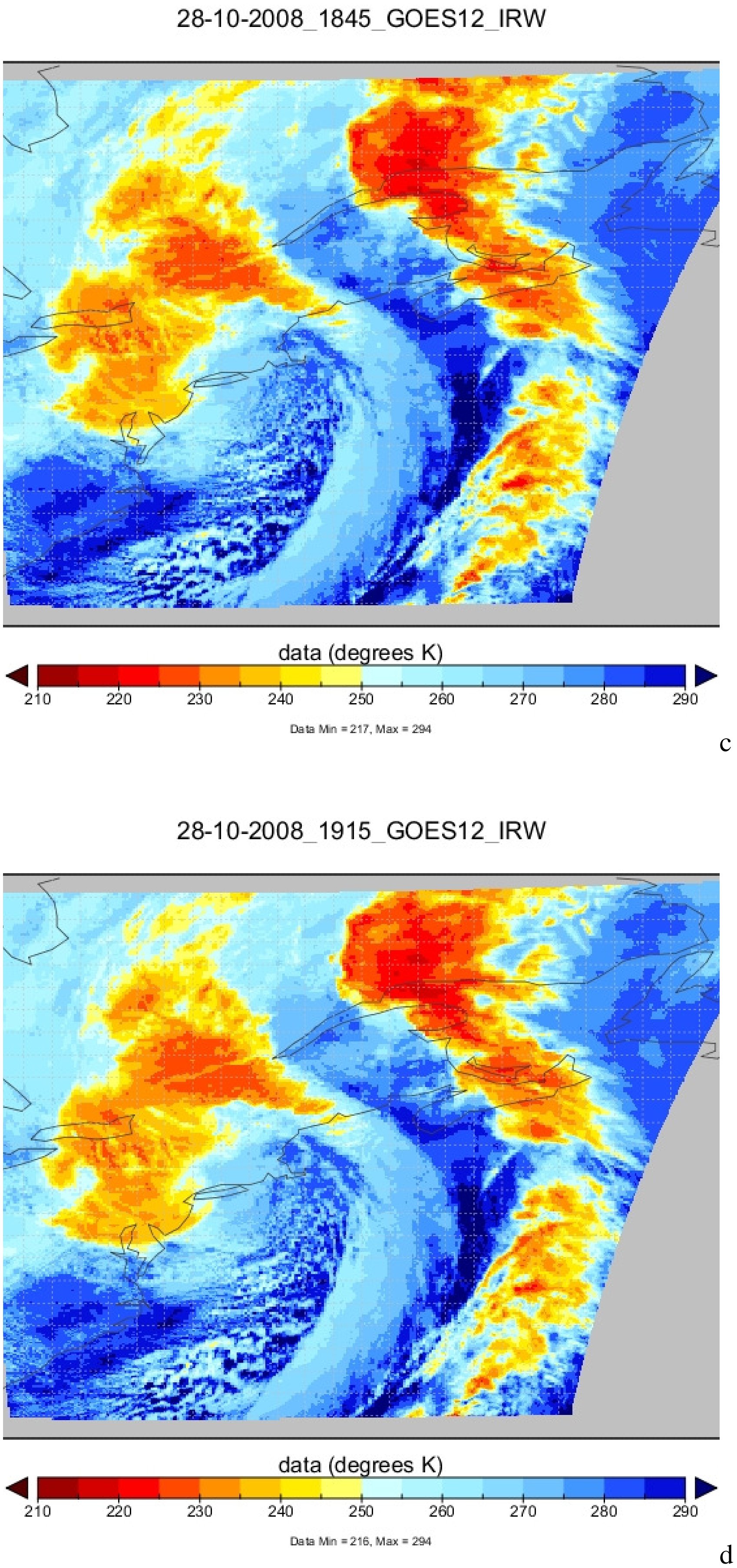
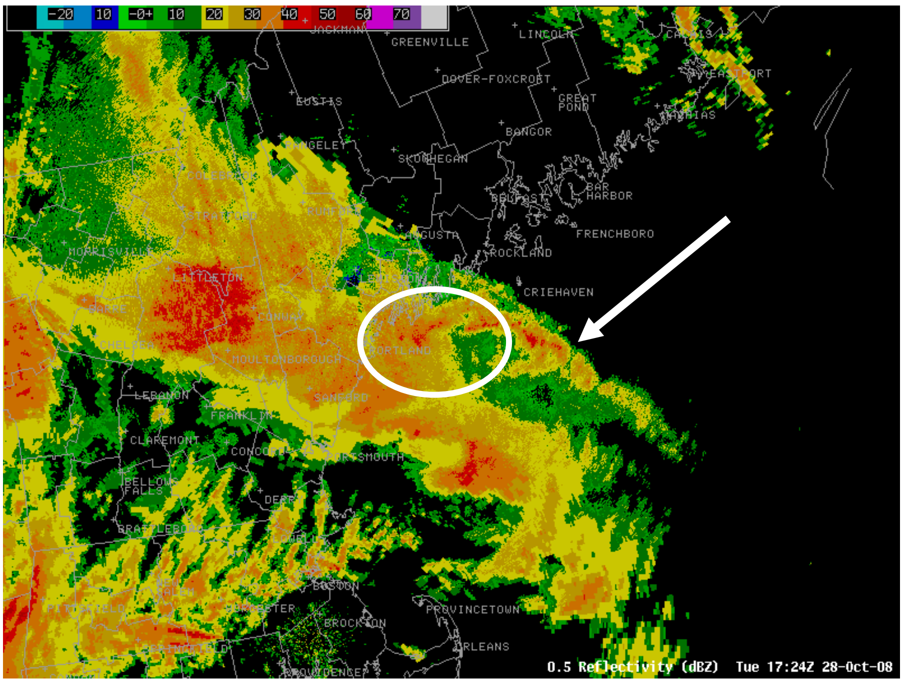


Figure 6: Color-enhanced GOES 12 IRW (channel 4) images for 28 October 2008: a)16:45, b) 17:45, c)18:45 and d) 19:15 UTC.

According to the cloud-top temperature (color shades in Figure 6), the most intensive cloud development was taking place within the triple point of the frontal system and the occlusion cloud-head. Cold front shows mostly warmer, water clouds, however some convective clouds with top temperature below 230K were developing within the frontal zone of the cold front.

Radar images show frontal precipitation passing over Boothbay from 17 to 19 UTC (at 19 UTC the front has already passed over the area of interest). From the appearance of the rain band it seems that no severe convection was taking place at the time of the event (Figs. 7 a-c), but there were some convective clouds embedded in the frontal cloud-band with maximum reflectivity 40-50 dBZ. Ground reports suggest that some showers and lightning were reported at the time of meteotsunami event.

Radar image at 17:24 UTC shows a line of high reflectivity (squall-line?), preceding the front, approaching the coast (marked by arrow in Fig 7a). Frontal cloud band (highest reflectivity values circled) reached the harbor at about 18 UTC (see 18:12 UTC radar image). Another maximum of reflectivity reached the coast at 18:48 UTC (about 45 minutes later).



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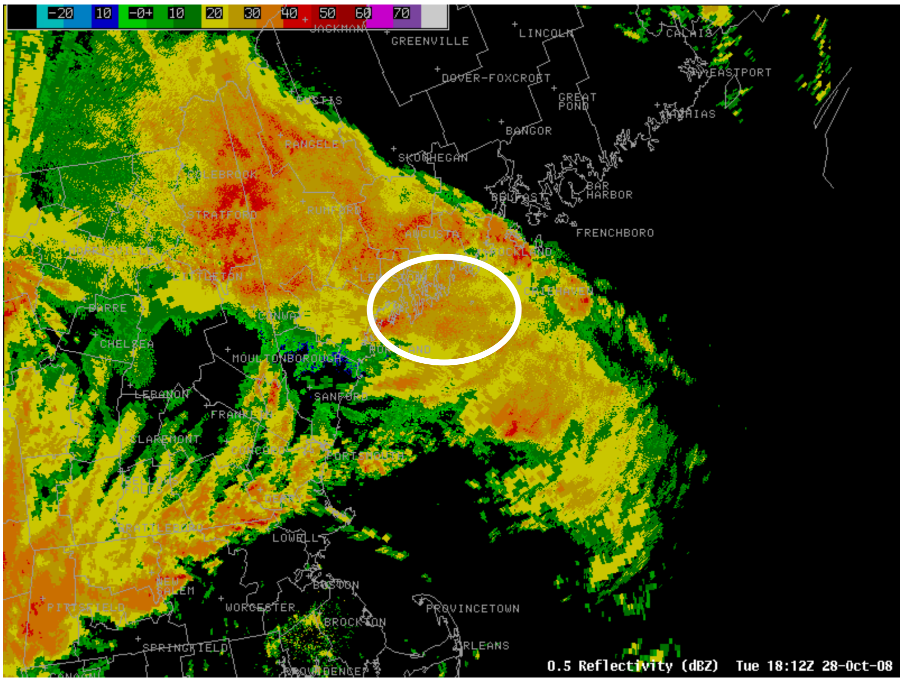

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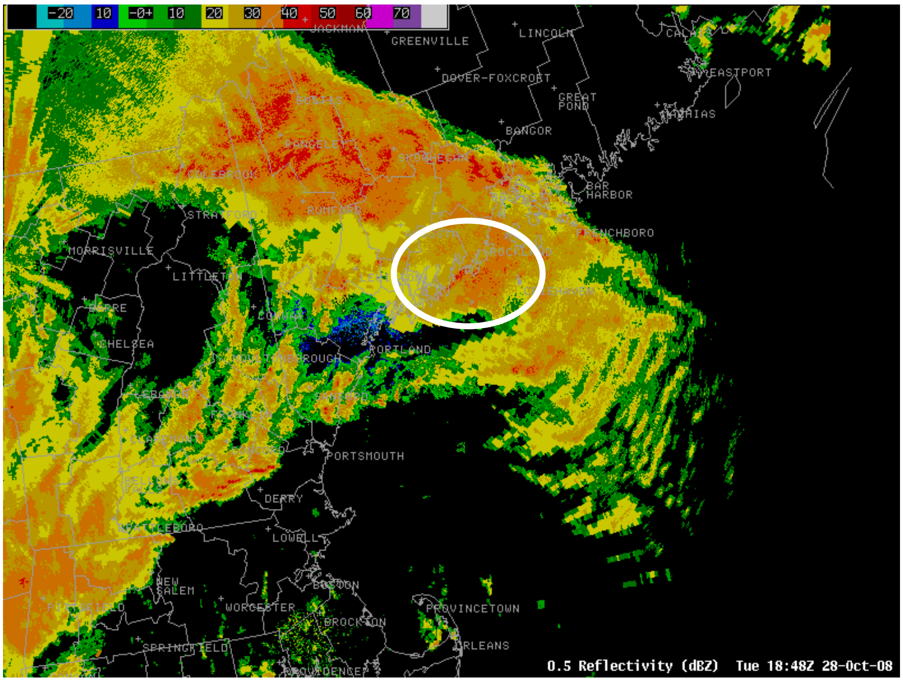
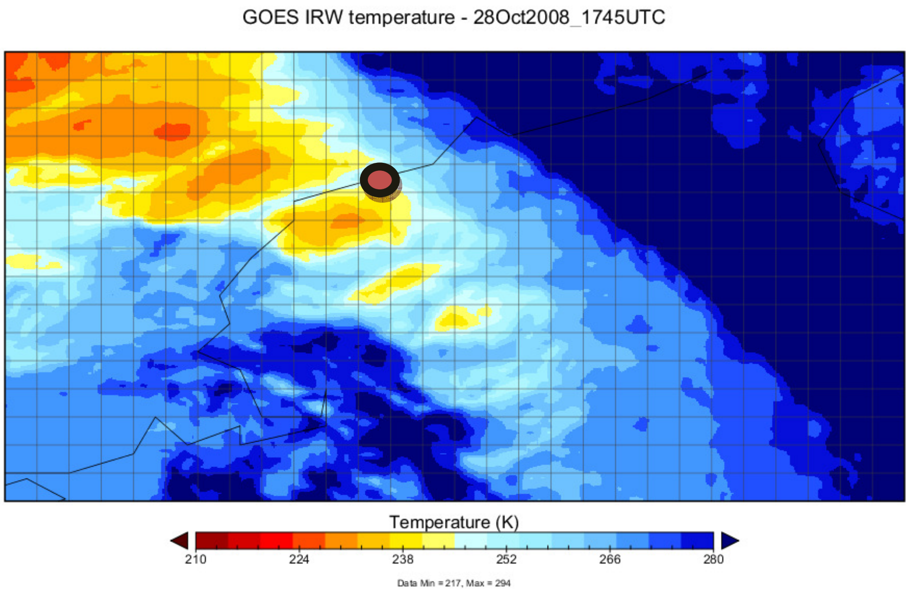


c

Figure 7: Composite radar reflectivity (dBZ) on 28 October 2008. a)17:24, b)18:12, c)18:48 UTC.

What can be seen is that the period between the high reflectivity features reaching the coast was cca 40-45 minutes, about two times a period of wave oscillations reported by the eyewitnesses. However, radar reflectivity features do not reveal possible cause of the wave formation.

Although satellite images do not show any extreme convection, some convective clouds developed within the cold front and moved over the area of interest, as revealed by the following images (Figs. 8 a-c). Location of Boothbay harbor is marked with a circle.



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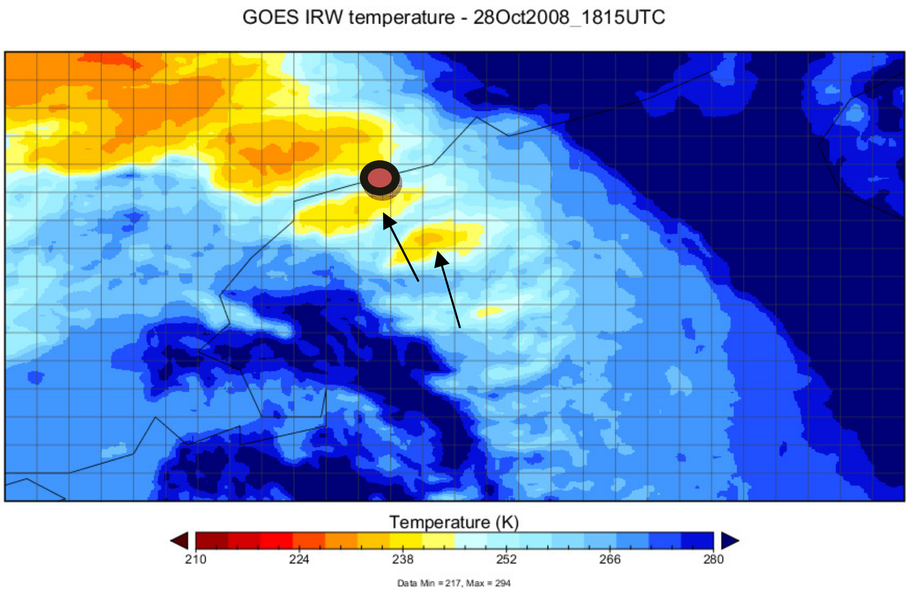

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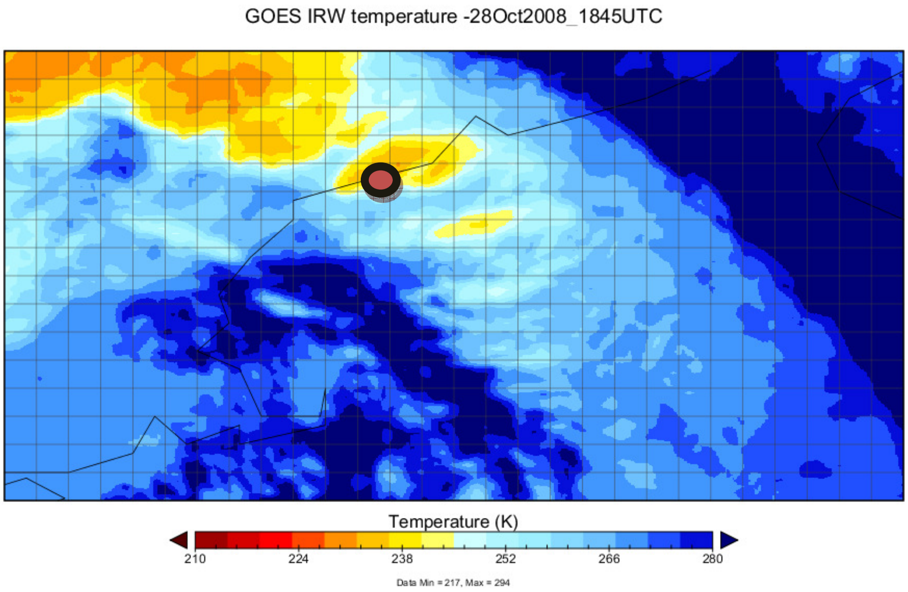
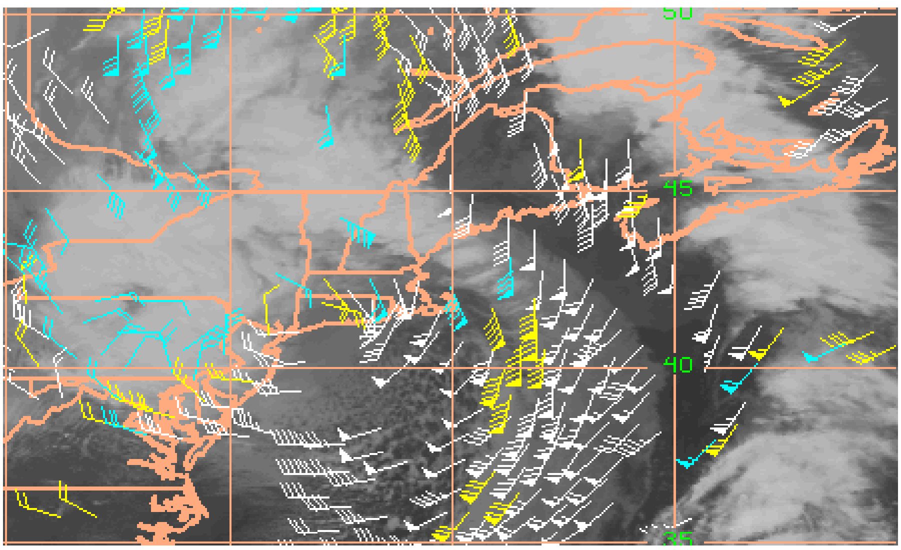


c

Figure 8: Color-enhanced GOES 12 IRW (channel 4) images on 28 October 2008. a) 17:45, b)18:15, c)18:45 UTC.

Cloud motion velocity estimated from these data is app. 30-32 m/s (vectors marked at the 1815 UTC image, Figure 8b). This speed is somewhat larger than the phase speed of the atmospheric waves estimated from the pressure gauge data. The direction near the location of meteotsunami event was app. 320 (SE to NW) which is in the agreement with the estimation from the pressure data.

The velocity of the movement can also be seen from the following wind fields, calculated from cloud movement in different levels:



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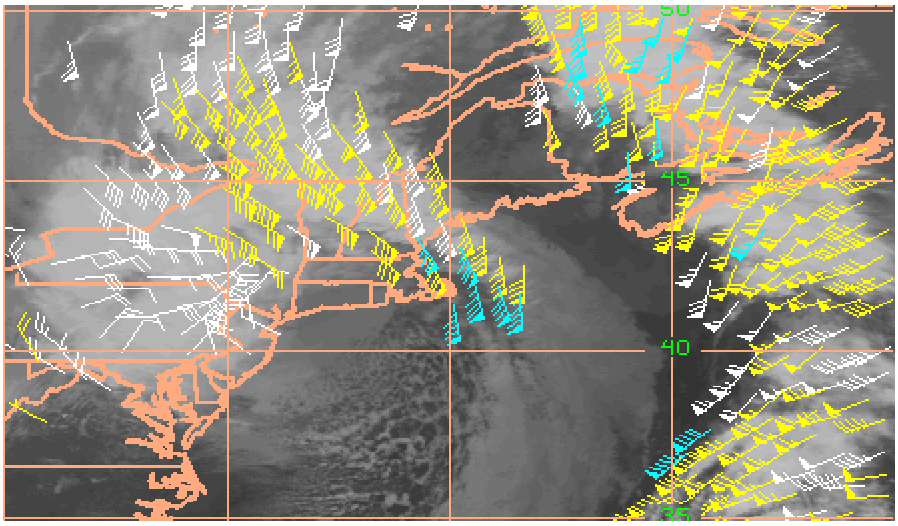


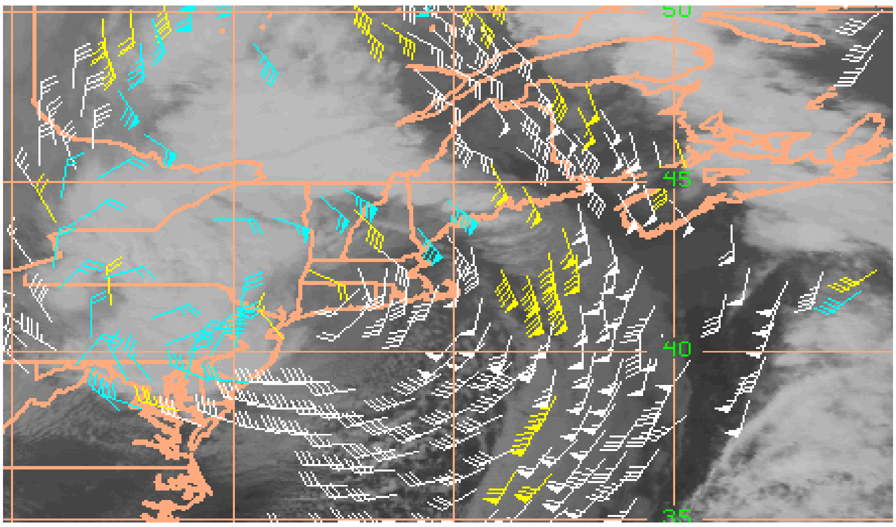
b

Figure 9: Winds calculated from satellite data for 28 October 2008 17:32 UTC.

a) mid-levels: blue (400-500 hPa), yellow (501-600 hPa), white (601-700 hPa);

b) upper levels: blue (100-200 hPa), yellow (201-300 hPa), white (301-400 hPa).

Winds at cloud-top heights (upper-tropospheric winds) have SSE direction and speeds between 40 and 45 m/s whereas winds in the mid-troposphere have S direction and speeds between 20 and 45 m/s. At 19:02 (Figure 10) also mid-tropospheric winds turned to SSE direction and upper-tropospheric winds to SE direction, with speed remaining between 30 and 45 m/s.



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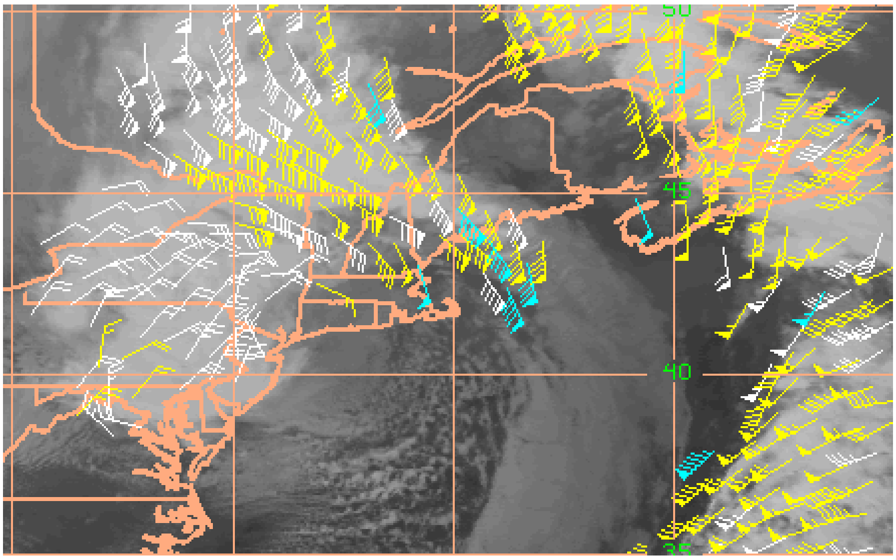

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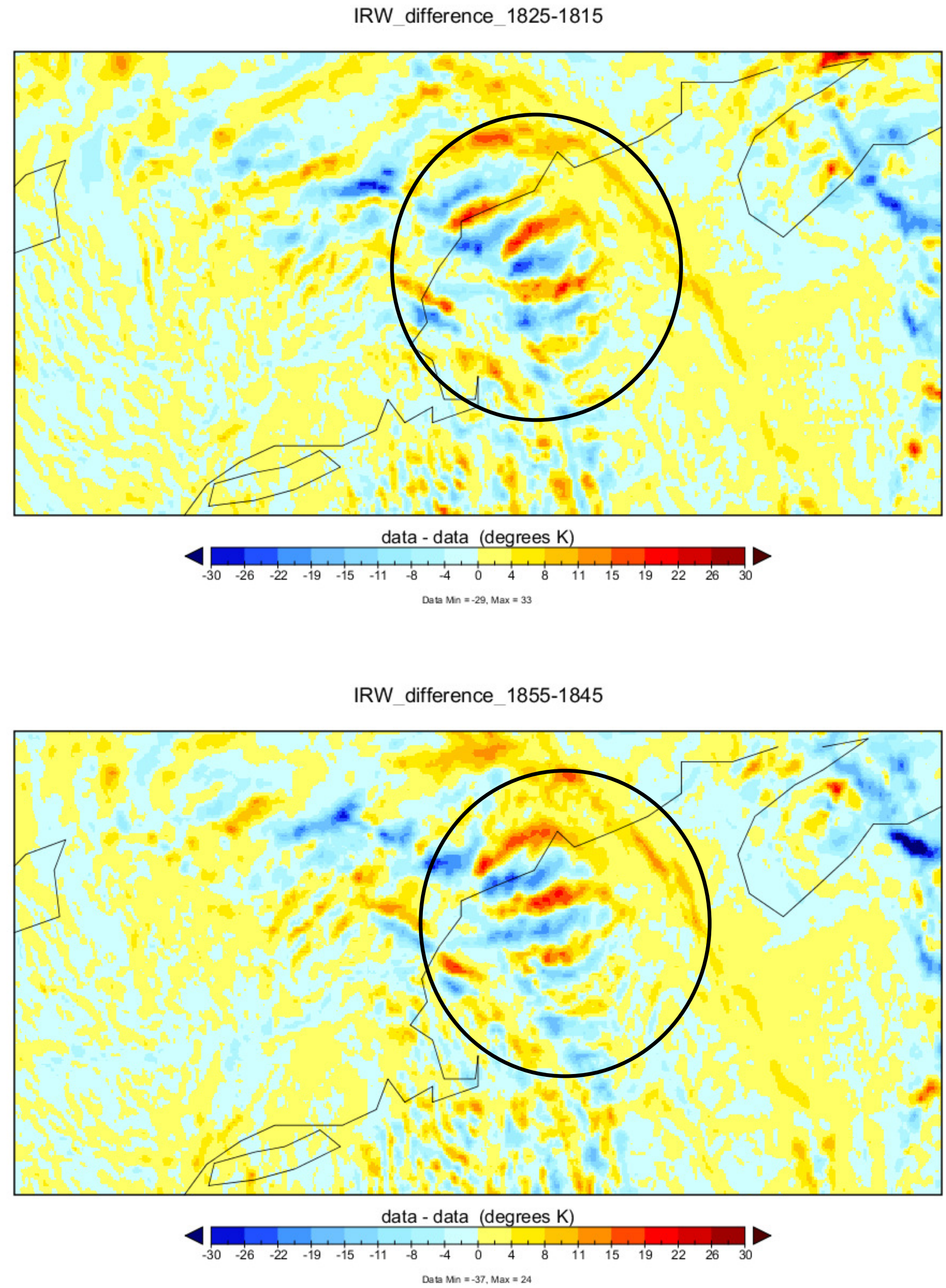
Figure 10: Winds calculated from satellite data for 28 October 2008 19:02 UTC.

a) mid-levels: blue (400-500 hPa), yellow (501-600 hPa), white (601-700 hPa);

b) upper levels: blue (100-200 hPa), yellow (201-300 hPa), white (301-400 hPa).

Besides these, some additional structures can be observed in the satellite data. First of all, single channel images in Figure 8 show a wave-like pattern within a cold front, moving relatively to the front in south-easterly relative stream.

This feature is even more pronounced a difference between two successive images is calculated. When the images 10 minutes apart are used, wavelike pattern is clearly visible (Figure 11). What do these images mean: very large positive difference (red in Figure 11) means that the temperature in the later image was much higher (warmer) than the one in the image before at the same spot. In other words in the image before there were clouds at the spot where in the later image there are no clouds (or less clouds). And vice versa for the blue area, which is area where the temperature in later image is lower (clouds) then in the image before (no clouds).



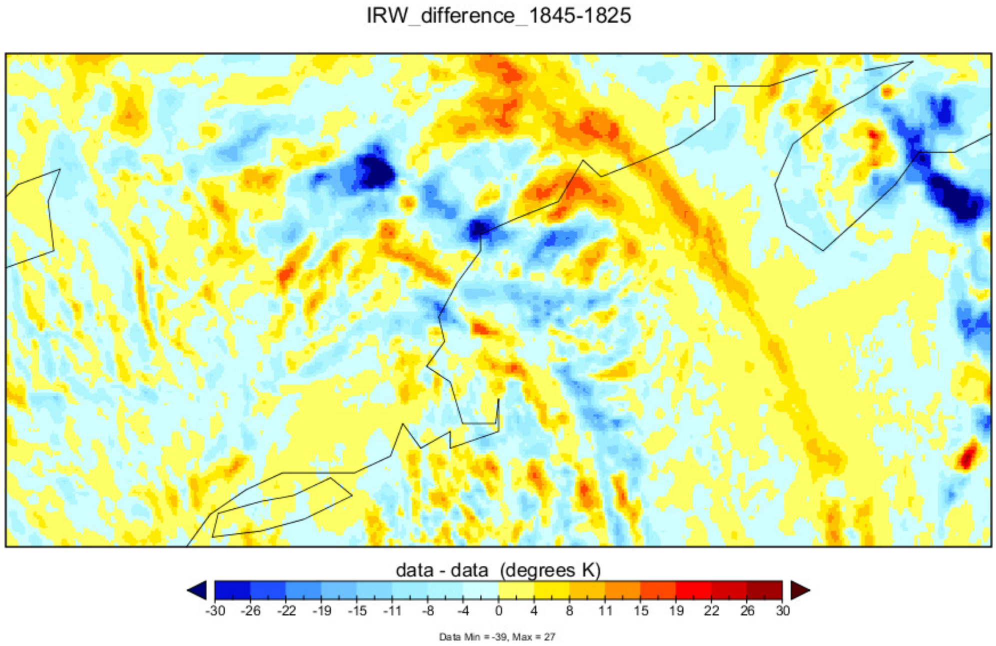
a

b

Figure 11: Temperature differences between two successive GOES 12 IRW satellite images. a) 28 October 2008 between 18:25 and 18:15 UTC, b) 28 October 2008 between 18:55 and 18:45 UTC

What has to be noted is that this pattern exists only over the sea close to Boothbay and over the coast, but not very far inland. This wave-like pattern could be found on all calculated difference images starting from 16 UTC and ending after 20 UTC.

Another interesting thing can be noted if 20 minutes interval is used: the wave-like pattern is not visible any more (or at least not that prominent)! (Figure



12)

Figure 12: Temperature differences between GOES 12 IRW satellite images at 28 October 2008 between 18:45 and 18:25 UTC

So, it seems there was a wave-like feature embedded in the cold front, moving relatively to the movement of the front, from SE to NW. The period between the maximum and minimum of cloud-top temperature seems to be 10 minutes, which would be very much in the agreement with wave period observed in Boothbay. Another feature that can be observed in the difference images is that the wave-like pattern has a quasi-constant width.

This feature resembles the feature of atmospheric gravity waves. For the atmospheric gravity waves to have influence on the sea surface they must be trapped vertically. For the AGWs to be trapped in the lower atmosphere there must be a vertical boundary that prevents the AGWs from escaping into higher levels. This can be a low-level temperature inversion or a vertical wind shear layer. For the AGWs to propagate over long horizontal distances, they must also be trapped sideways. This is achieved by horizontal wind shear generated, for example, by wind jets and wakes in the lee of mountain ranges. In this case the AGWs travel in a wave duct or wave guide and often propagate horizontally over distances of several hundreds of kilometers. (Cheng i Alpers, 2010)....

In case of the Boothbay event radiosounding data from two stations were available for the analysis of the state of the atmosphere (Figure 13). These are two stations closest to Boothbay – one in Chatham, south (upstream) of Boothbay, and the other in Gray, west from Boothbay.

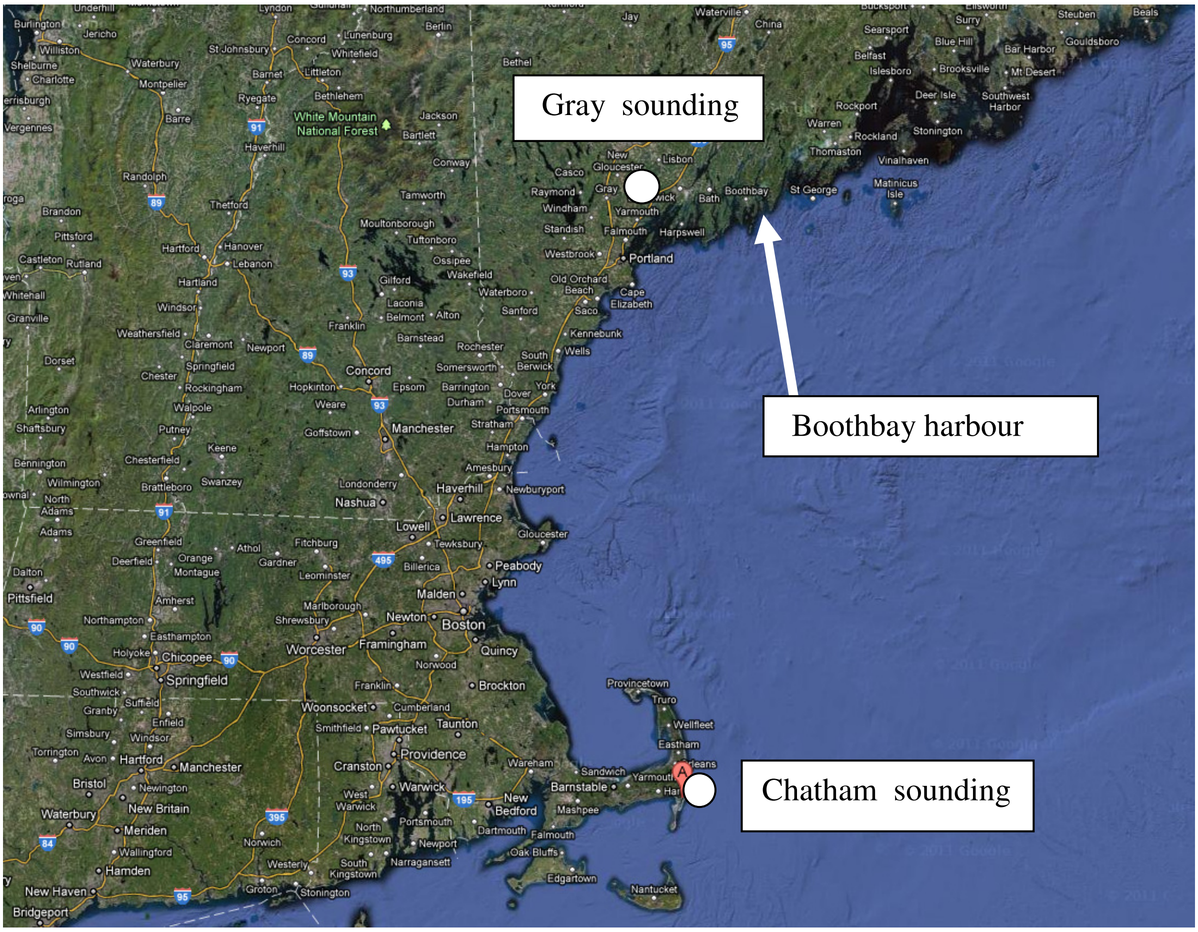
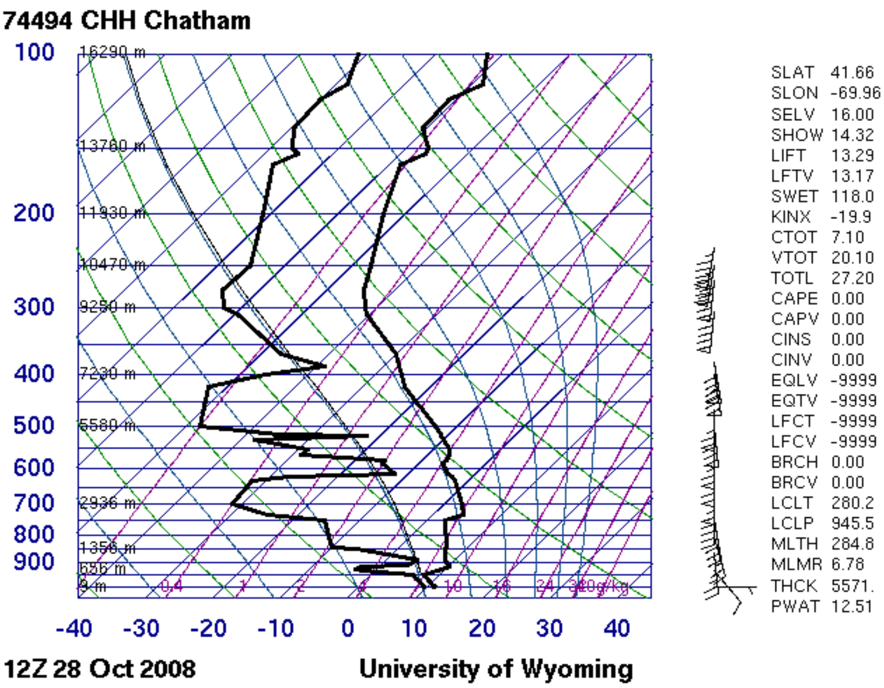


Figure 13: Locations of the radiosounding stations in Chatham and Gray



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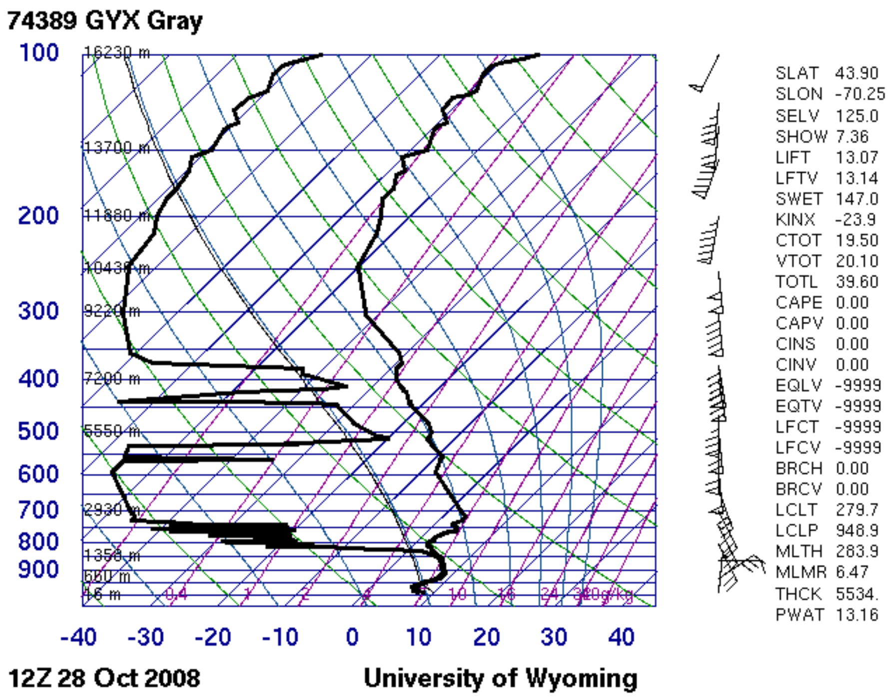


b

Figure 14: Skew-T Log-P diagrams for Chatham (a) and Gray (b) for 28 October 2008 12 UTC.

In both temperature profiles in Figure 14 temperature inversion can be found at about 650 m and another inversion, more pronounced for Gray sounding, is found between 1600 and 2500 m. There is also a wind shear layer in low atmosphere seen for both stations. Potential temperature profile (Figure 15) suggests that the atmosphere was stable which favored trapping of the AGW if they existed.

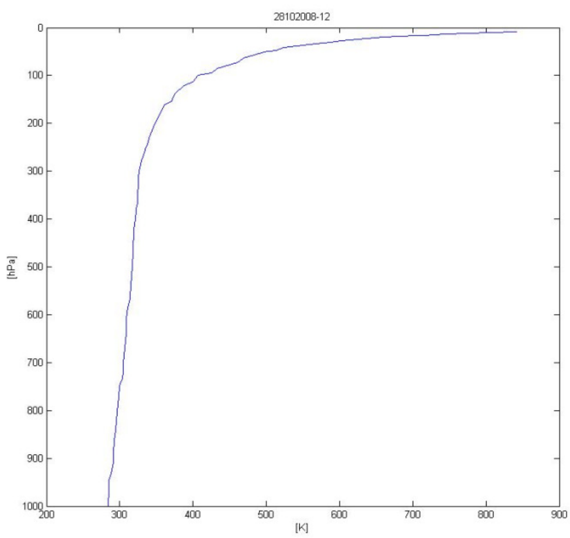


Figure 15: Profile of the potential temperature for Chatham sounding data, 28 October 2008, 12 UTC.

The feature that speaks in favor of the horizontal trapping of the AGWs is seen in Figure 16. Regions of high wind shear are found on both sides of the zone in which wave-like structure occurred. These zones of high shear might have served as boundaries, keeping wave-motion trapped and enabling the disturbance to travel over large distance.

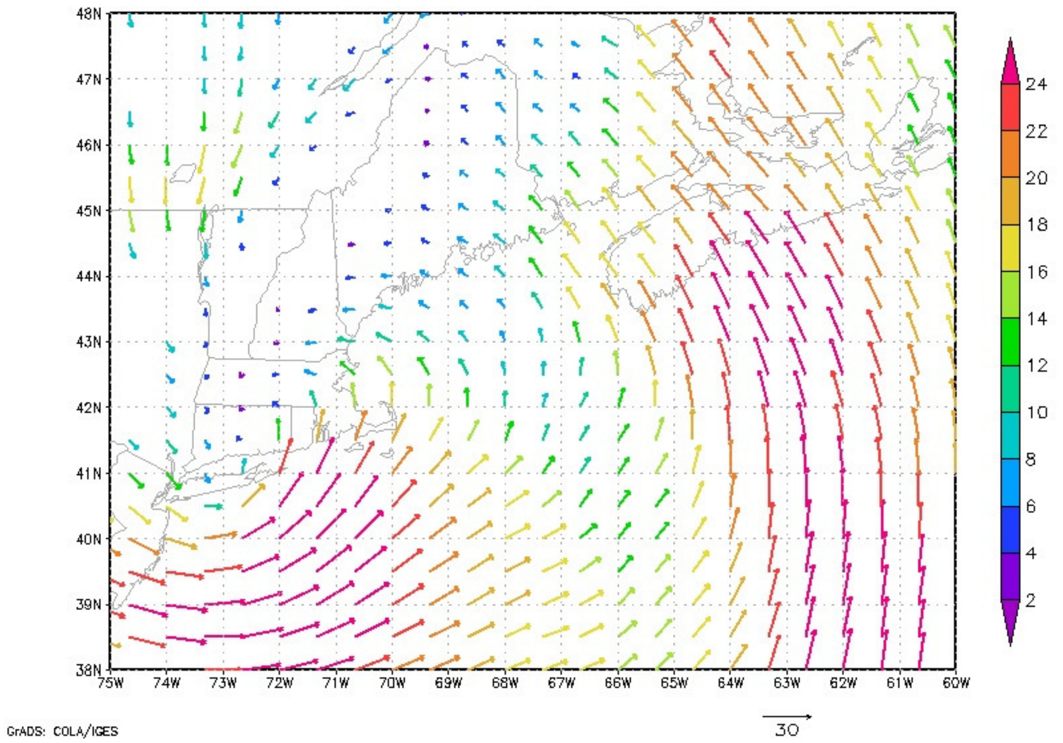


Figure 16: MERRA reanalysis data for 28 October 2008, 18 UTC: Wind velocity at 950 hPa level.

Discussion

In the existing analyses of the Boothbay harbor meteotsunami it is mentioned that there was another frontal passage on the 26 October 2008 (two days before). That frontal passage was associated to the pressure oscillation that can be seen in Monserrat et al preliminary analysis (their Fig 6), but the sea level oscillations related to that event had smaller amplitudes (their Figure 7) and did not cause any serious effect in the harbor. To understand the difference between the two systems, satellite data were analyzed. Frontal system that passed over Boothbay on 26 October 2008 is seen in Figure 17. Cloud top temperatures, compared to the ones in Figure 6 for the Boothbay event, were considerably lower (colder), meaning that the height of the frontal clouds was much larger in the front on 26th than in the one on the 28th.

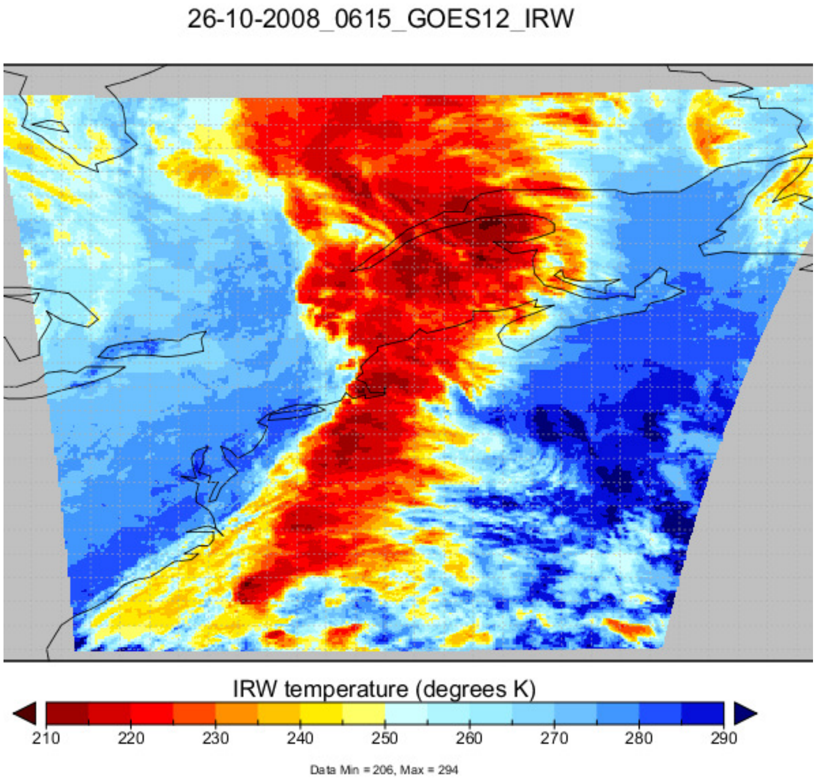
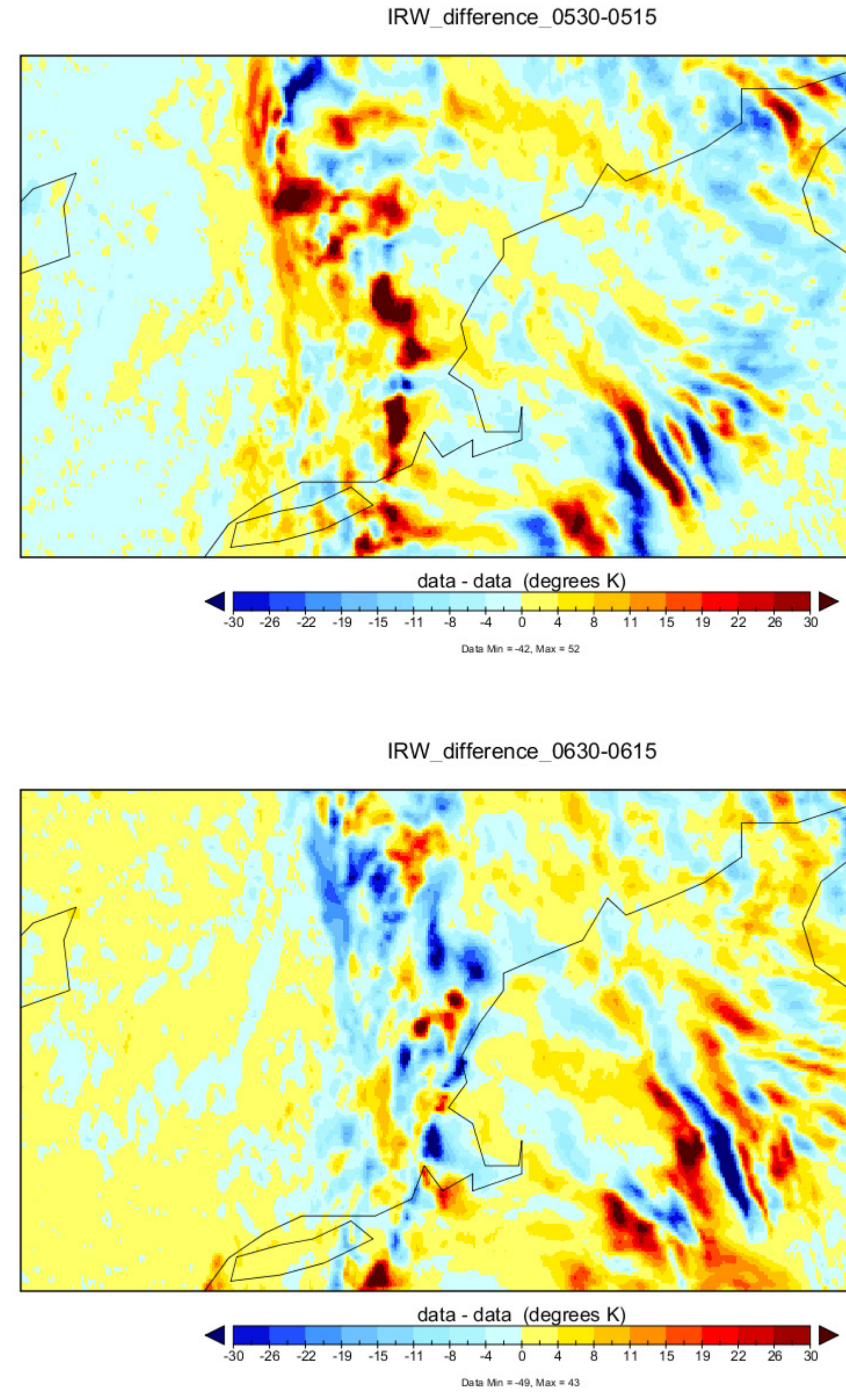


Figure 17: Color-enhanced GOES 12 IRW (channel 4) images for 26 October 2008, 0615 UTC.

Besides the fact that the front on the 26th was much more convective than the one on the 28th, the most important difference between the two frontal systems is seen in Figure 18. The differences between two successive images on 26th do not show the wave-like pattern observed on the 28th. There is a similar pattern, but far away from the Boothbay harbor. Besides that, as seen in Figure 19 the wind field could not serve as the horizontal boundary even if the wave pattern would have existed. Contrary to the Boothbay event case, here the wind speed at 950 hPa level was largest around the region of the harbor. What can also be noted here is that the wind in the lower levels was almost perpendicular to the wave-like pattern seen SE of Boothbay, whereas in case of Boothbay event the wind was directed along or parallel to the wave pattern , so it could serve as a transportation mechanism bringing the anomaly to the coast, which was not the case for the 26th.



a

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Figure 18: Temperature differences between GOES 12 IRW satellite images at 26 October 2008: a) between 05:30 and 05:15 UTC and b)between 06:30 and 06:15 UTC

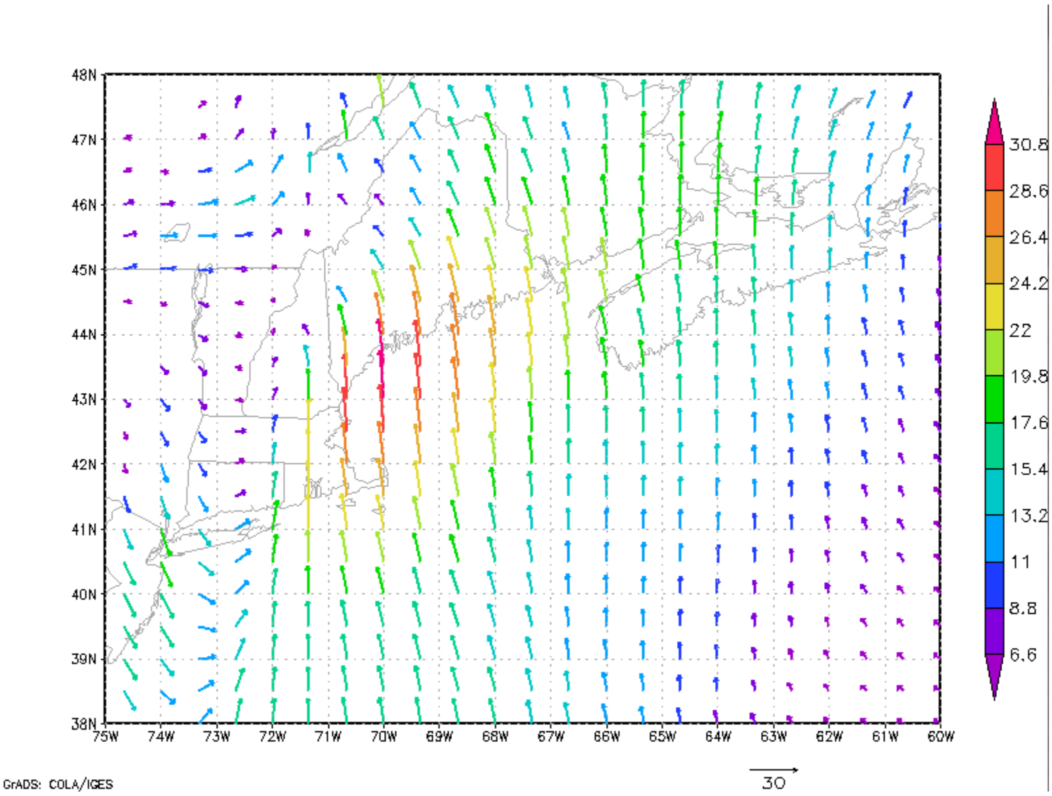

Figure 19: MERRA reanalysis data for 26 October 2008, 06 UTC: Wind velocity at 950 hPa level.

It can be concluded that in case of Boothbay meteotsunami event a wave-like feature, possibly atmospheric gravity waves, were embedded in the frontal band that passed over the region of interest. The AGWs were ducted by temperature inversion and a layer of wind shear vertically and by the regions of high horizontal wind shear from both sides horizontally, enabling the anomaly to travel over large distance keeping its wave characteristics. The period between the maximum and minimum was 10 minutes, which is in agreement with the observation of high sea level every cca 20 minutes in the harbor.

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DHMZ, Croatia

C. M. Cheng and W. Alpers, 2010: Investigation of trapped atmospheric gravity waves over the South China Sea using Envisat Synthetic Aperture Radar images. International Journal of Remote Sensing Vol. 31, 4725–4743.