A Rogue Wave Event at Middle Cove Beach, Newfoundland

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1. Introduction

On Wednesday, August 27, 2008, a 1008 mb low formed over the Labrador Sea, approximately 300 nm south of Greenland and tracked northeastward toward Iceland where it began to deepen under the influence of an upper low (Fig. 5). On Thursday, August 28, 2008 the low became quasi-stationary south of the Denmark Strait between Iceland and Greenland and over the next 30 hrs had its central pressure rapidly deepen from 1000 (Fig. 5) to 970 mb (Fig. 7). By the morning of Friday, August 29, 2008 the storm began to slowly weaken; only filling by 17 mb over the next 24 hrs (Fig. 9). The weakening of the isallobaric component of the wind allowed the normally weaker northeasterly winds to strength to storm force.

A wind field approximately 120 nm wide across the Denmark Strait grew toward the southwest at approximately 10 kts from the morning of Friday, August 29, 2008 to the morning of Saturday, August 30, 2008 (Figs 12 and 13). The storm force northeasterly wind field created a fetch effectively 120 nm wide and 550 nm long with a duration of over 24 hours.

By the evening of Friday, August 29, 2008, the winds over the fetch box had created a sea state with a significant wave height of ~13.5 m and a peak period of ~16 seconds in the generation area (see Fig. 16). These waves left the generation region as swell and travelled southwestward with the longest period swell travelling at ~35 kts. Located about 1200 nm to the southwest, the northern Avalon Peninsula of Newfoundland and the Northern Grand Banks observed the first long period waves around noon local time on Sunday, August 31, 2008. The bulk of the wave energy arrived later in the afternoon and persisted overnight with the significant wave height diminished to size to ~3.5m due to angular spreading and dispersion (Fig 22).

Sea state forecasts produced by the NWP guidance verified well with observations.

On the afternoon of Sunday, August 31, 2008, this swell with a significant wave height of ~3.5m and period of 16 seconds began to transition from a deep water wave to a shallow water wave in ~200 m of water, about 126 km northeast of Middle Cove Beach. Off of Middle Cove Beach the swell became a pure shallow water wave in a depth of 15-20 m of water and began to shoal over the local bathymetry in a depth of 4-6 m. During the swell's peak the resulting wave set-up raised the water level over 8 m above mean sea level.

2. Shallow Water Waves

As waves move into shallower water, d < L/2, frictional drag begins to dissipate the total wave energy. The group speed of the wave is now not only period dependent but is also depth dependent. From the dispersion equation the group speed can be calculated from the following formula.

$$(1) \qquad c_g = \frac{gT}{2\pi}\tanh\left(\frac{2\pi d}{L}\right)$$

As the wave continues to move into shallow water, where the depth of the water is equal to or less than 1/20 of the wave length, the dispersion equation is no longer dependent on the wave period and therefore is no longer dispersive. The group velocity of the shallow water waves is now only dependent on the depth of the water.

$$(2) \qquad c_g = \sqrt{gd}$$

The decrease in kinetic energy due to the shallowing wave is converted to potential energy by increasing the wave height in order to conserve the total energy of the wave (assuming no dissipation). The growth in wave height as a function of changing wave speed can be calculated from the following formula.

$$(3) \qquad H_2 = \sqrt{\frac{c_{g1}}{c_{g2}}}H_1$$

Waves that are approaching the shore from an angle other than perpendicular to the shore will refract towards perpendicular. The wave crest that is closest to the shore will interact with the shallower water first and slow down. The wave crest that is further from the shore will generally retain its speed and as a result turn towards the shore.

2.1 Shoaling Effects

Because wave period is almost always conserved the decrease in wave speed due to the decrease in water depth decreases the wave length but increases the wave height. This process, known as shoaling, continues until the wave reaches a point that it becomes unstable and finally breaks. The height of the shoaling wave before it breaks is dependent on the wave period, deep water wave height, H_s, and slope of the bathymetry during shoaling. For cases of a constant near shore slope is known (m > 0, where m is the near shore slope), the breaker height is estimated as (Goda 1970 as cited in CERN, 1984).

$$(4)\ H_B = H_s\left[.575m^{0.031}\left(\frac{H_s}{1.56*T^2}\right)^{-0.254}\right]$$

Figure 1 below shows a nomogram that has been developed through empirical studies to calculate the shoaling factor via the beach slope and deep water wave steepness, where Goda uses $H_0^{\prime}$ to denote H_s:

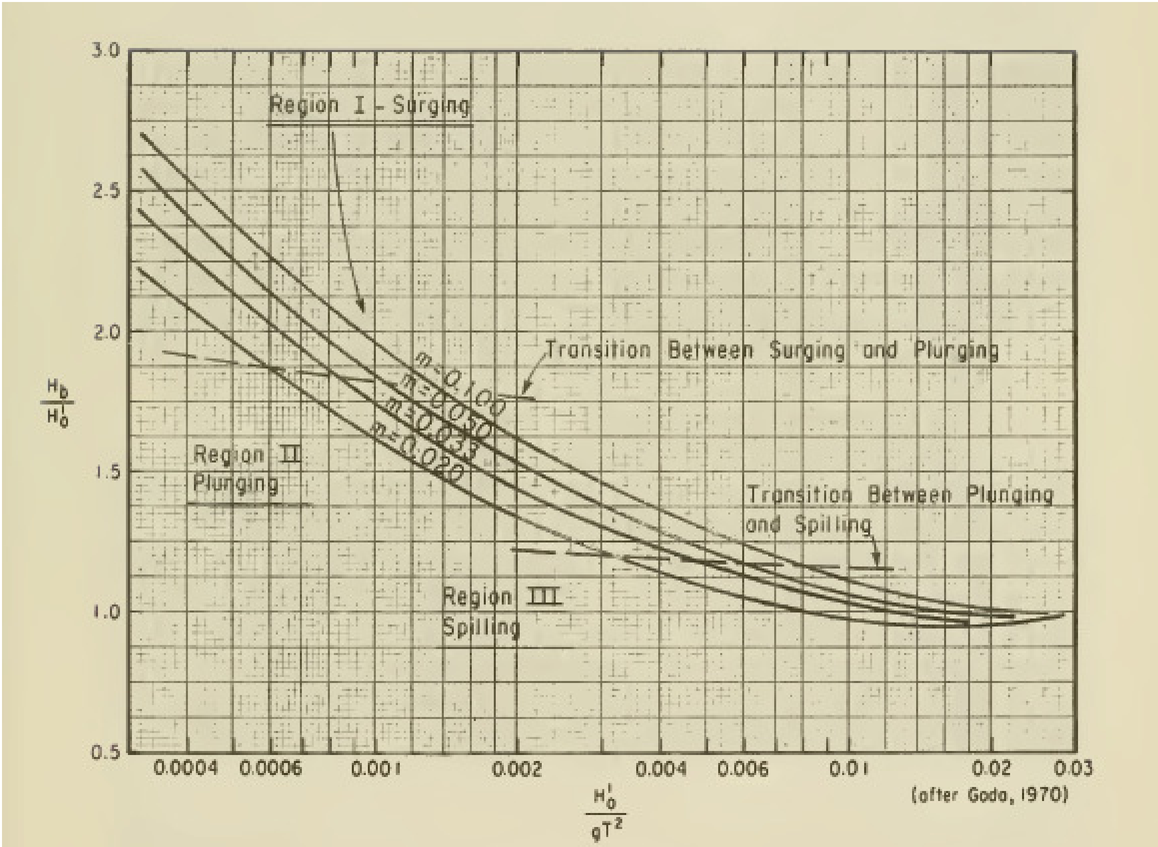

Figure 1. Shoaling factor nomogram

The depth of water in which the wave will break, d_B, can be determined using another empirical equation (Weggel 1972 as cited in CERN, 1984);

(5) $$d_B = \frac{H_B}{b - a\left(\frac{H_B}{gT^2}\right)}$$

Where, $a = 43.75\left(1 - e^{-19m}\right)$

and $b = \frac{1.56}{\left(1 + e^{-19.5m}\right)}$

Figure 2 shows how breaker depth depends on shallow water wave steepness, $H_B/L = H_B / (g*T^2)$ and near shore slope. For low steepness waves the breaker index, d_B/H_S, is bound by the theoretical value of 1.28 as the beach slope approaches zero (horizontal) and twice the theoretical value, 0.64, (the sum of the perfectly reflected and incident component) as the beach slope reaches infinity.

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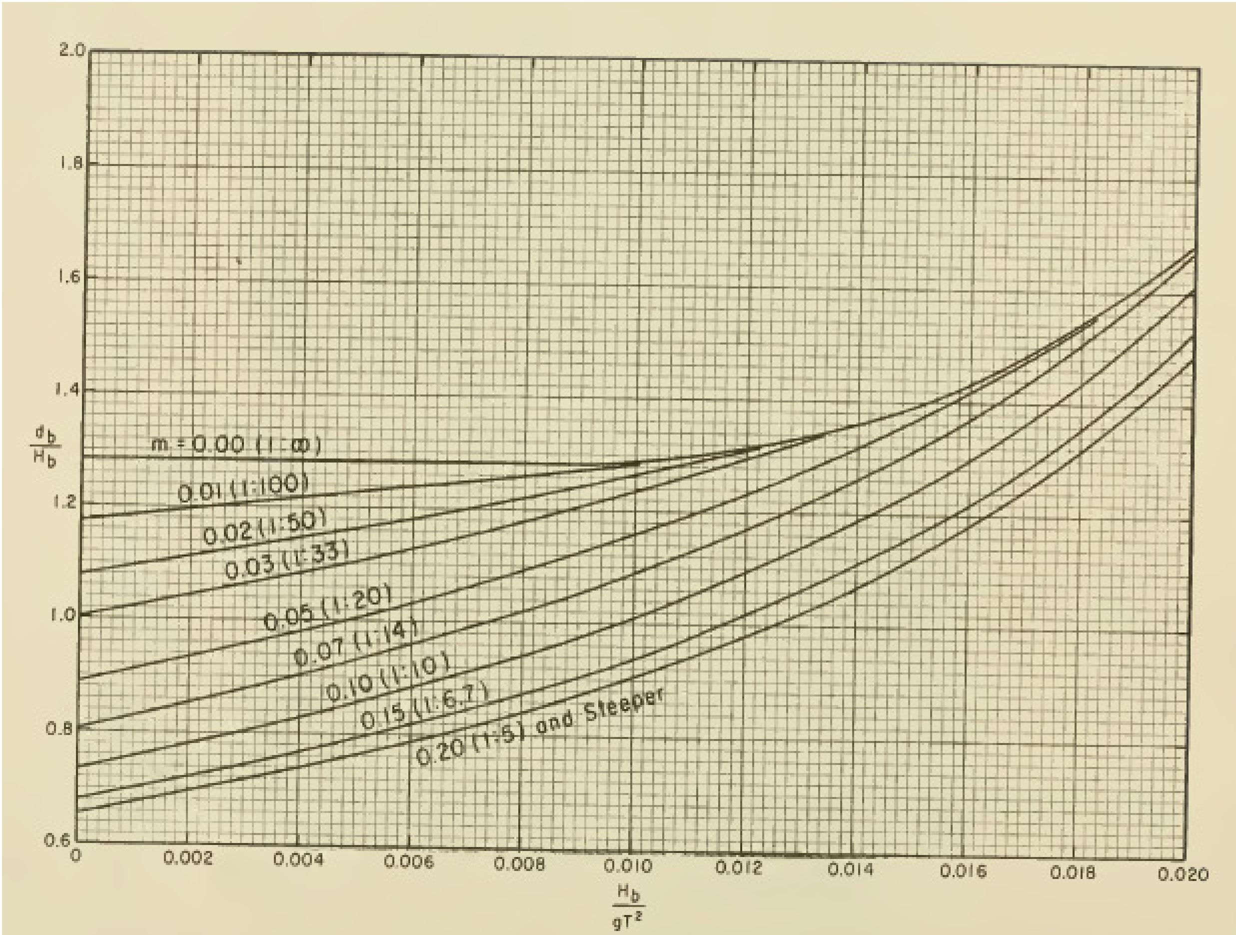


Figure 2. Breaking Depth factor nomogram (CERC 1984)

2.2.1 Wave Set-Up

After the wave has broken the incoming bore of water flows towards the coastline faster than the return flow can flow out. The piling up of water in the surf zone raises the water level up the beach. The wave set up at the shore has been estimated few different waves. A simple vertical rise in water is between 10 and 15% of that of the breaking wave height was used by in the Shoaling Wave Comet Module Comet 2006);

(6) wave set-up = (0.1-0.15)*H_B

Holthuijsen (as cited in Holthuijsen, Cambridge University Press, 2007) estimates wave set up as ;

(7) $$wave\_set\_up = \frac{5}{16} * \gamma * H_b$$

Where γ is the breaker depth index and can be found by dividing equation 5 by H_B, so that;

(8) $$\gamma = \frac{1}{b - a\left(\frac{H_B}{gT^2}\right)}$$

Battjes and Stive (1985)(as cited in Holthuijsen, Cambridge University Press, 2007) uses a relation dependent on deep water wave steepness.

(9) $\gamma = 0.5 + 0.4 * \tanh\left(33 * \frac{H_s}{1.56 * T^2}\right)$

2.2.2 Wave Run-Up

Wave run-up is the maximum vertical distance that any wave will run up the beach during the period of interest. Wave run-up is depended on many factors of which may be difficult to account for such as beach composition (grain size and distribution), variability in beach slope and water saturation. A crude estimation of the beach run-up from the largest 2% of the waves can be estimated as half the significant breaker height plus 50 cm (Comet 2006).

(10) wave run-up = $0.5*H_B + 0.5$

A more in depth estimate developed through an empirical study by Nielsen and Hanslow (1991), which takes foreshore slope, b, into account as well as deep water wave parameters;

(11) run-up= $1.19*b*(H_s*1.56*T^2)^{1/2}$ for $b > 0.1$

Figure 3 illustrates the some of the introduced parameters during the shoaling, wave run-up and wave set-up processes.

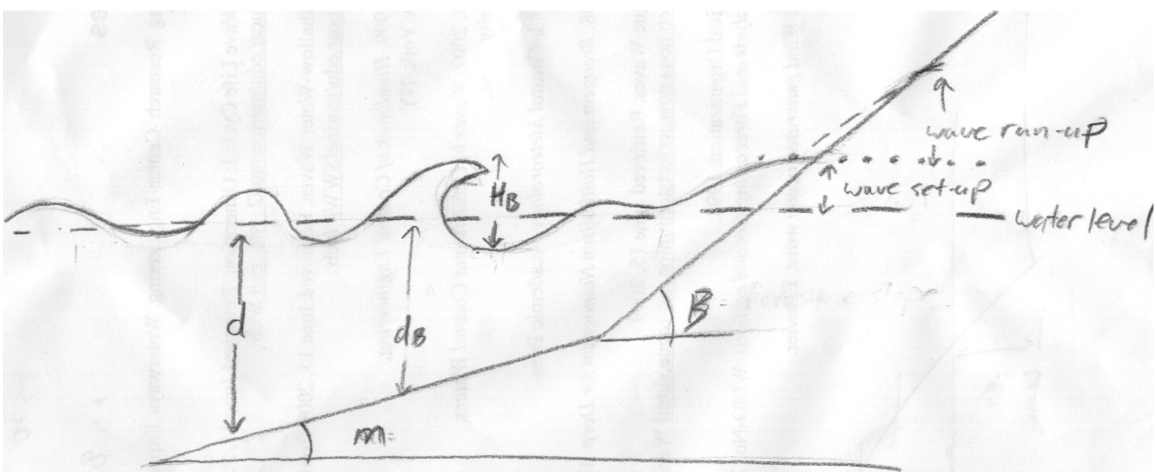


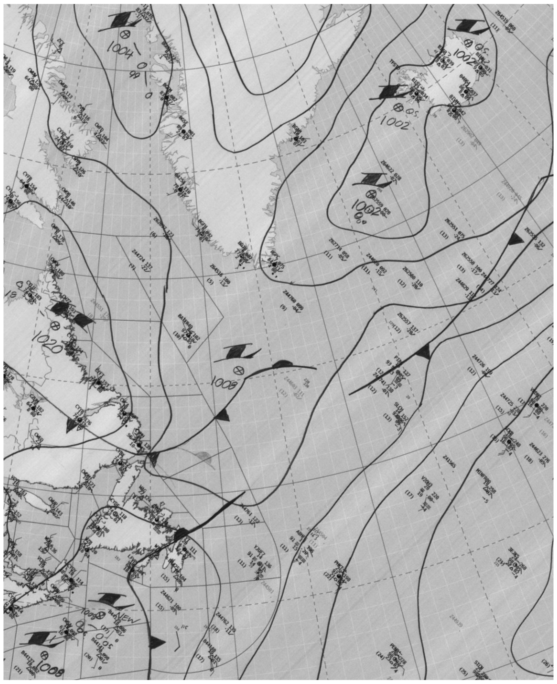
Figure 3.

3.0 Reanalysis

3.1 Synoptic Reanalysis

Using the surface analysis charts provided by the Atlantic Storm Prediction Centre, ASPC, the synoptic meteorological event can be reanalyzed.

On Wednesday, August 27, 2008, a relatively benign 1008 mb low formed over the Labrador Sea (Fig 4), approximately 300 nm south of Greenland and tracked northeastward toward Iceland, where it began to deepen under the influence of an upper low (Fig 5).



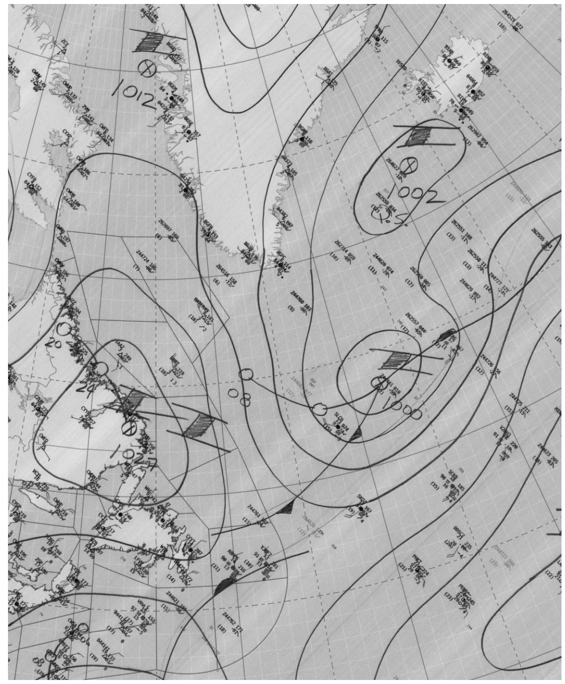
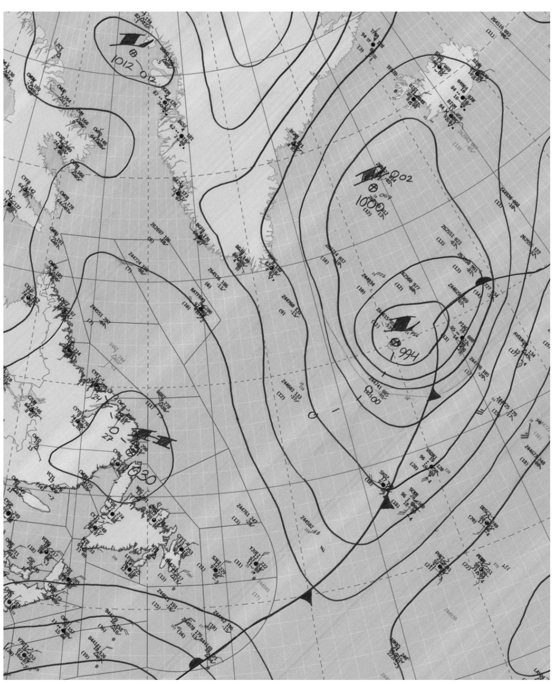


Figure 4. Surface analysis 2008-08-27 18Z, (ASPC 2008).

Figure 5. Surface analysis 2008-08-28 06Z, (ASPC 2008).

On Thursday, August 28, 2008, the low became quasi-stationary south of the Denmark Strait between Iceland and Greenland (Fig 6) and over the next 30 hrs had its central pressure rapidly deepen from 1000 to 970 mb (Fig 7).



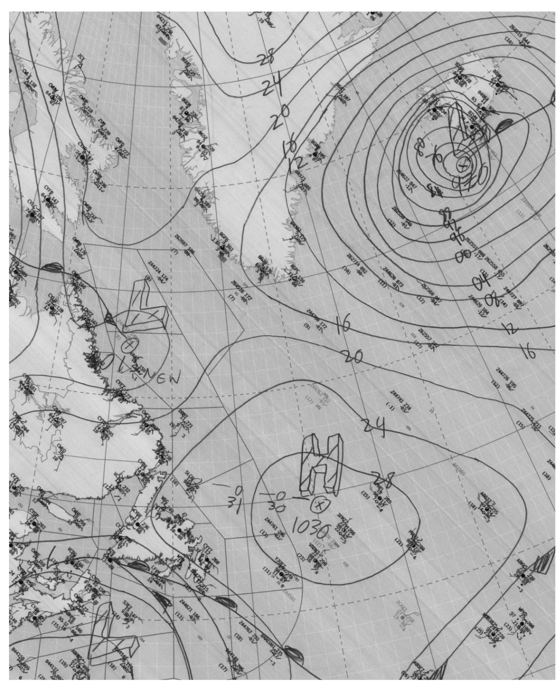


Figure 6. Surface analysis 2008-08-28 12Z, (ASPC 2008).

Figure 7. Surface analysis 2008-08-29 12Z, (ASPC 2008).

By the morning of Friday, August 29, 2008, the storm began to slowly weaken only filling by 17 mb over the next 24 hrs (Figs 8 and 9). The weakening of the isallobaric component of the wind allowed the normally weaker northeasterly winds to strengthen to storm force.

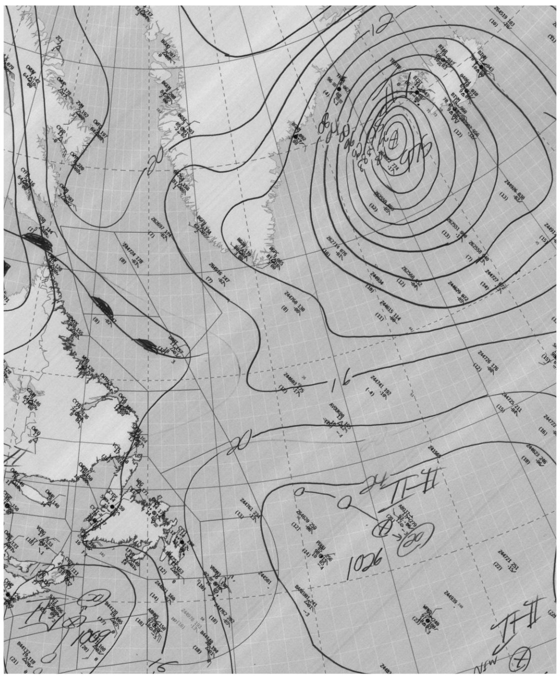


Figure 8. Surface analysis 2008-08-30 00Z, (ASPC 2008).

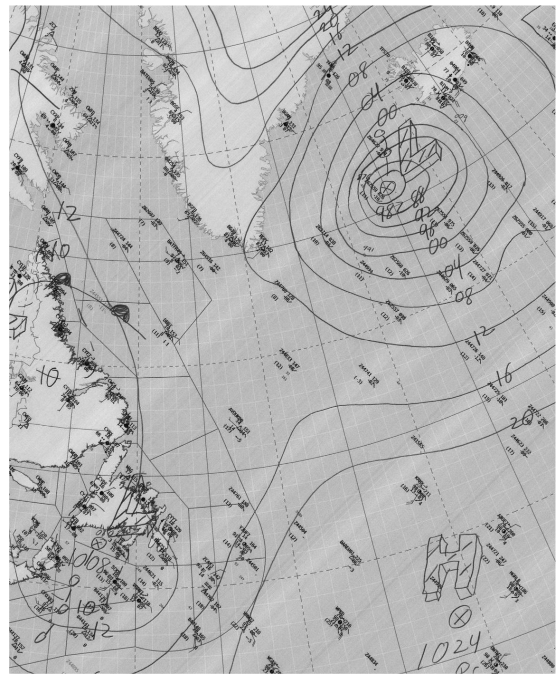


Figure 9. Surface analysis 2008-08-30 12Z, (ASPC 2008).

As the storm approached the Iceland the winds over the Denmark strait the QuikScat images, courtesy of Remote Sensing Systems (remss.com), observed began to strengthen to about 15 to 20 kts from the northeast (Fig 10 and 11).

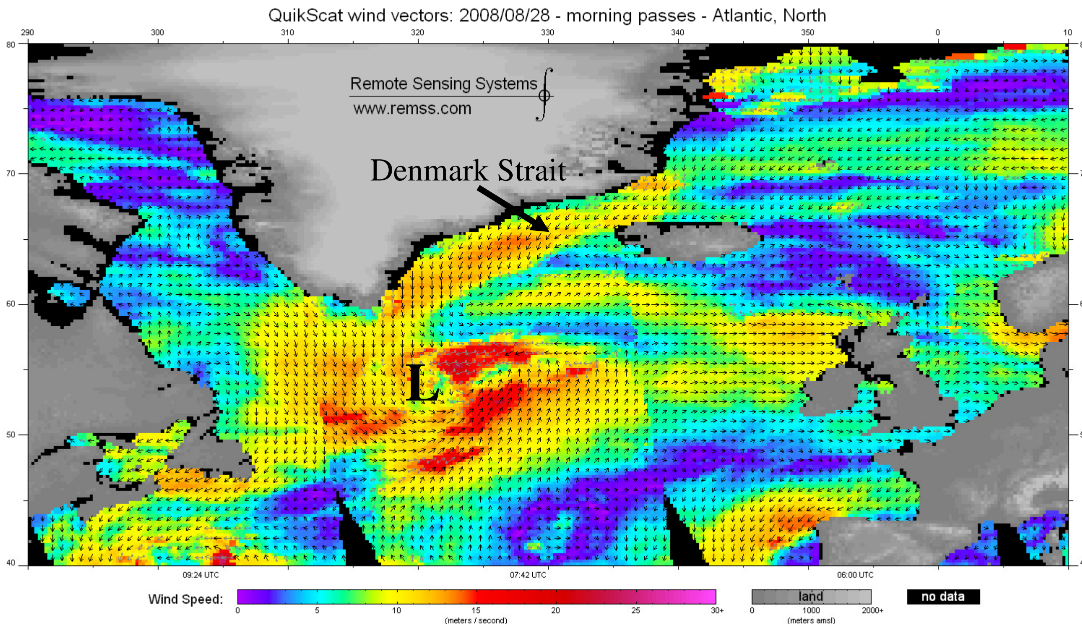


Figure 10. (www.remss.com, 2008)

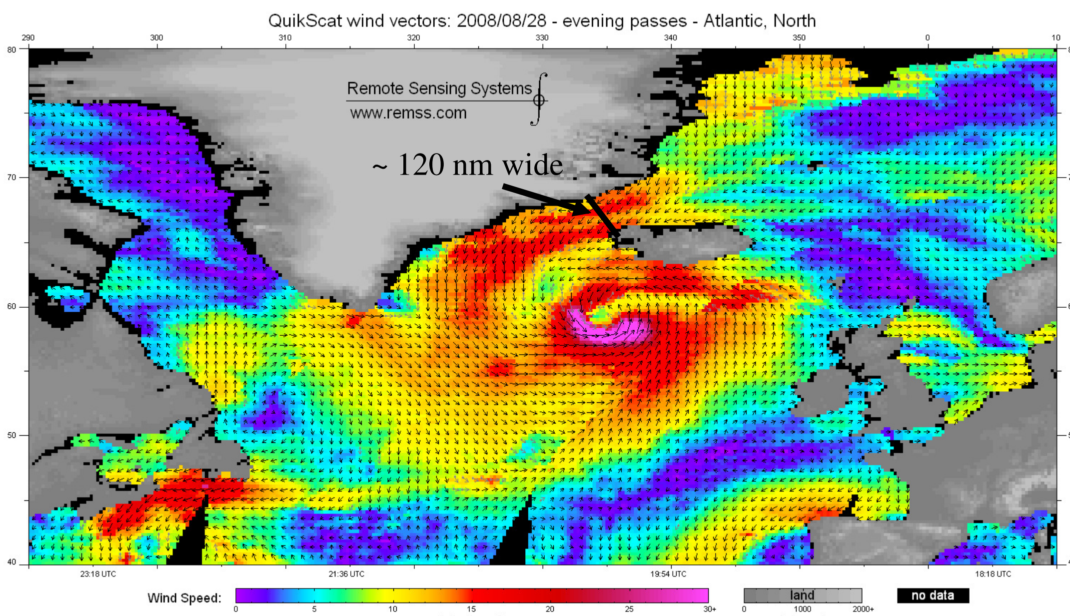


Figure 11. (www.remss.com, 2008)

On the evening of Thursday, August 28, 2008, a wind field with a fetch approximately 120 nm wide across the Denmark Strait and 300 nm long with an average wind speed of approximately 30 kts from the northeast had developed (Fig. 12).

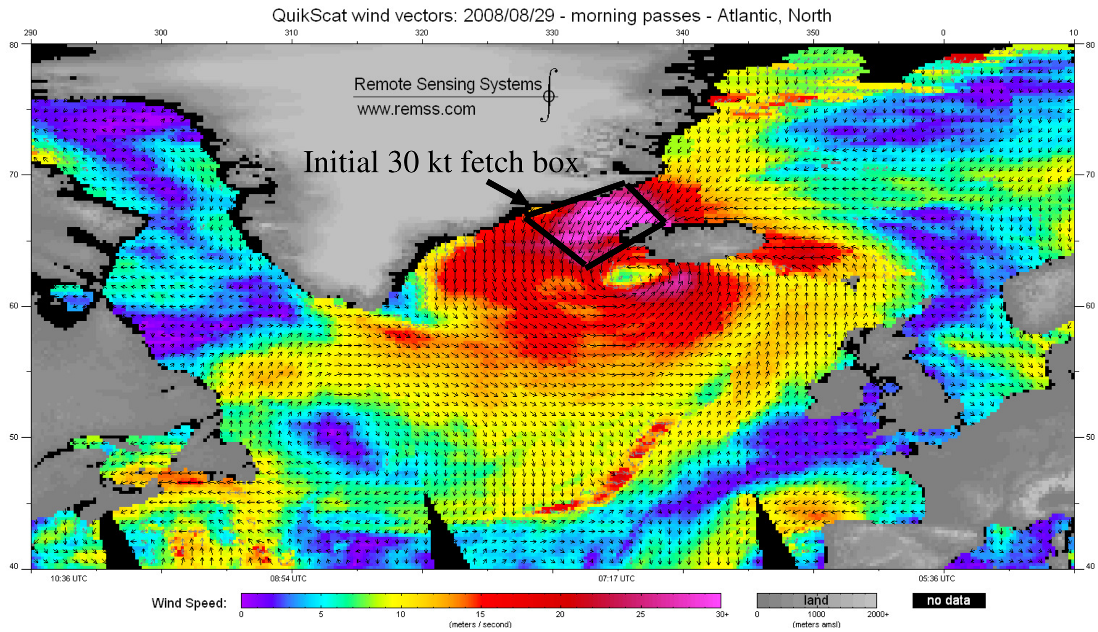


Figure 12. (www.remss.com, 2008)

The winds over this fetch strengthened to upwards of 60 kts by the following evening-pass on Friday, August 29, 2008, and grew toward the southwest at approximately 10 kts, reaching a further 250 nm to the southwest (Fig 13).

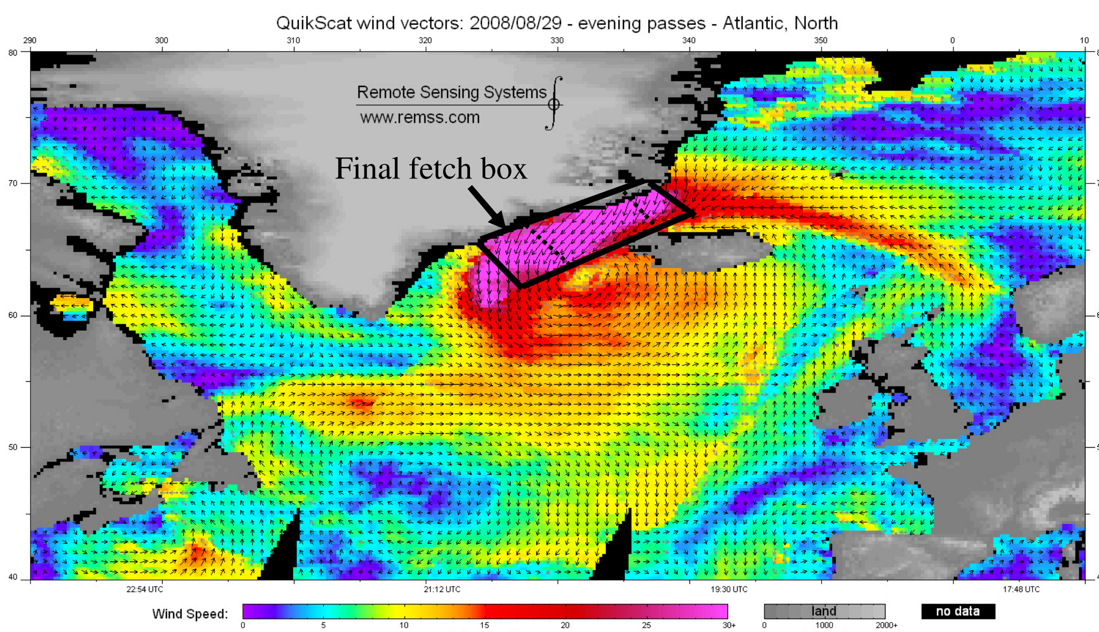


Figure 32. (www.remss.com, 2008)

By the morning of Saturday, August 30 2008, the winds had begun to subside and the effective fetch had grown to 550 nm in length (Fig 14).

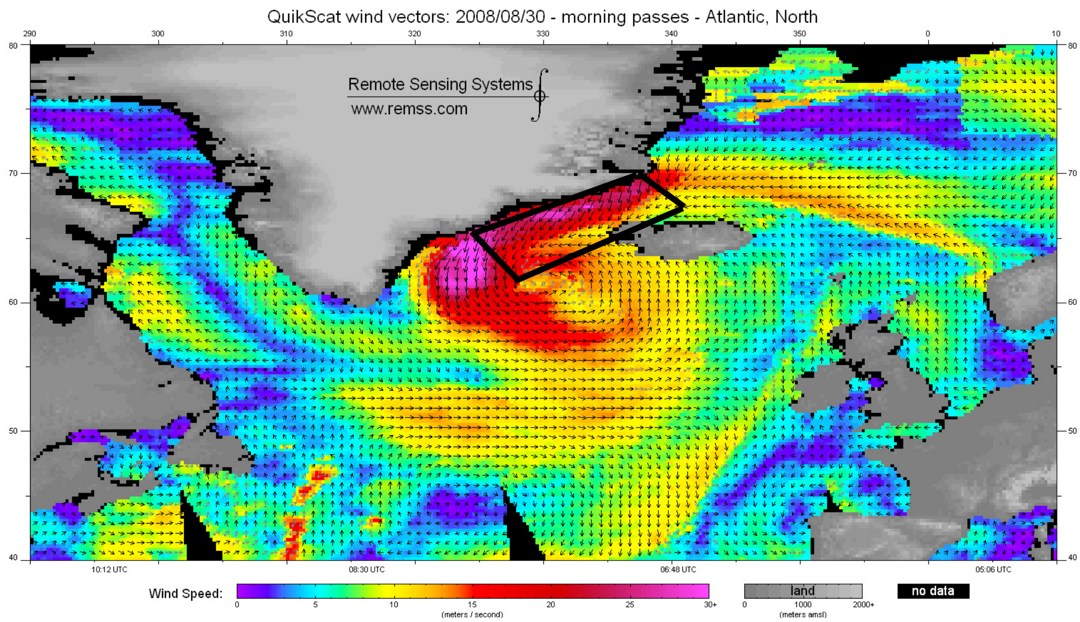


Figure 14. (www.remss.com, 2008)

3.2 Sea State Reanalysis

The wave analysis drawn by forecasters in the Atlantic Storm Prediction Centre (ASPC) in Dartmouth, NS and the numerical guidance provided by the MSC's WAM model shown in Figures 14 – 22 illustrates the dispersion of the swell into the north Atlantic towards Newfoundland.

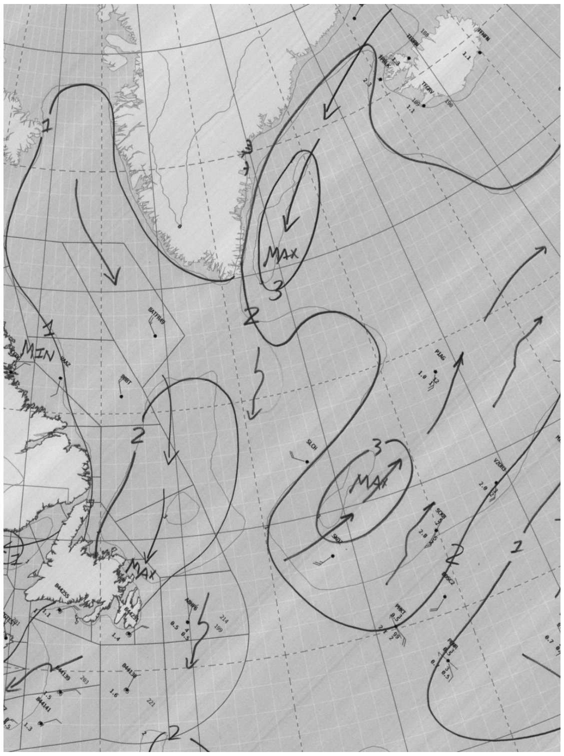


Figure 15. Sea state analysis 2008-08-28 06Z, (ASPC 2008).

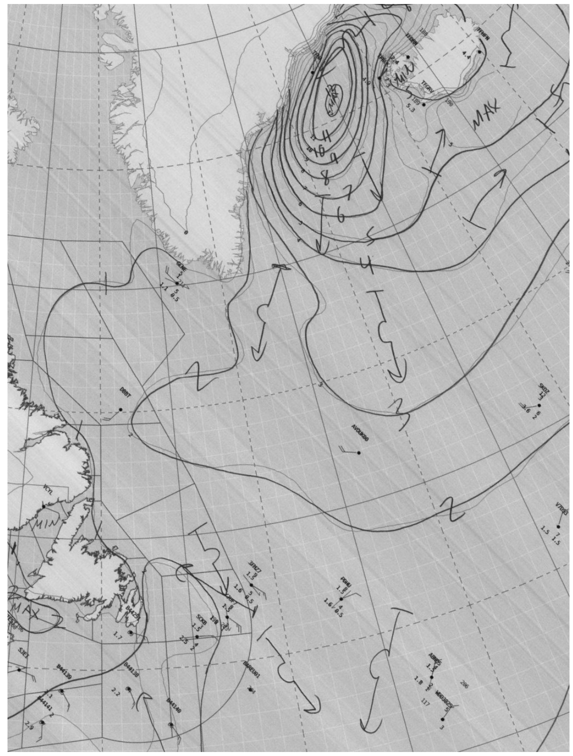


Figure 16. Sea state analysis 2008-08-29 18Z, (ASPC 2008).

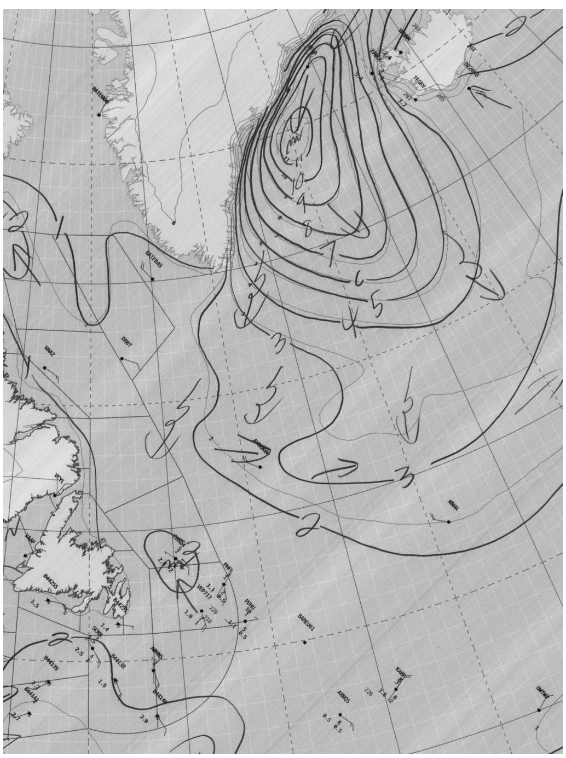


Figure 17. Sea state analysis 2008-08-30 06Z, (ASPC 2008).

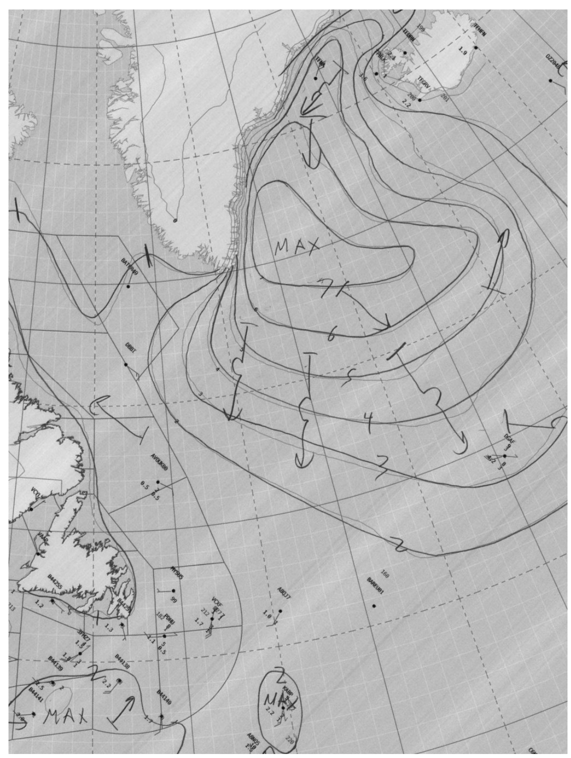


Figure 18. Sea state analysis 2008-08-30 18Z, (ASPC 2008).

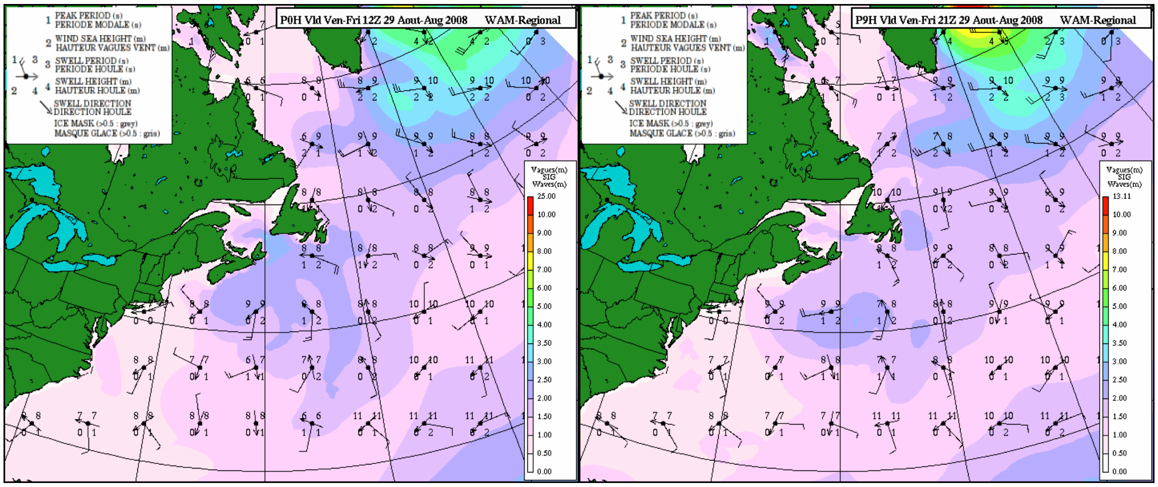


Figure 19. WAM Sea state forecast from the 12Z run on 2008-08-29 (CMC 2008)

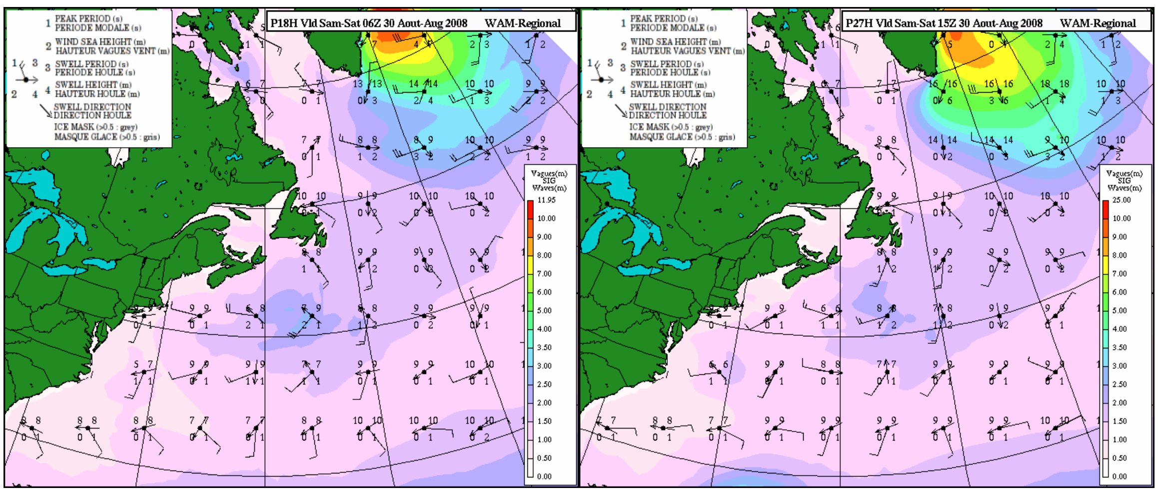


Figure 20. WAM Sea state forecast from the 12Z run on 2008-08-29 (CMC 2008)

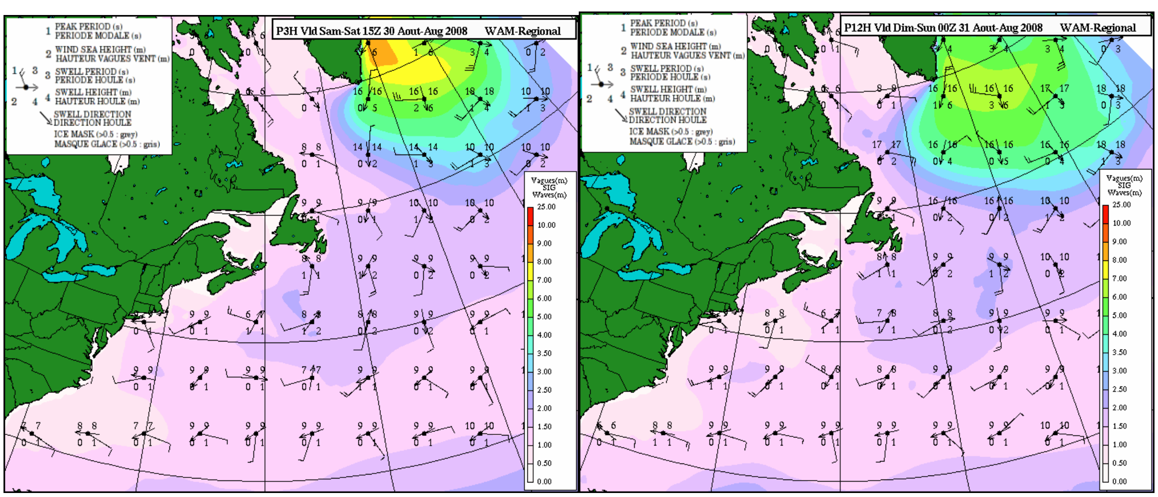


Figure 21. WAM Sea state forecast from the 12Z run on 2008-08-30 (CMC 2008)

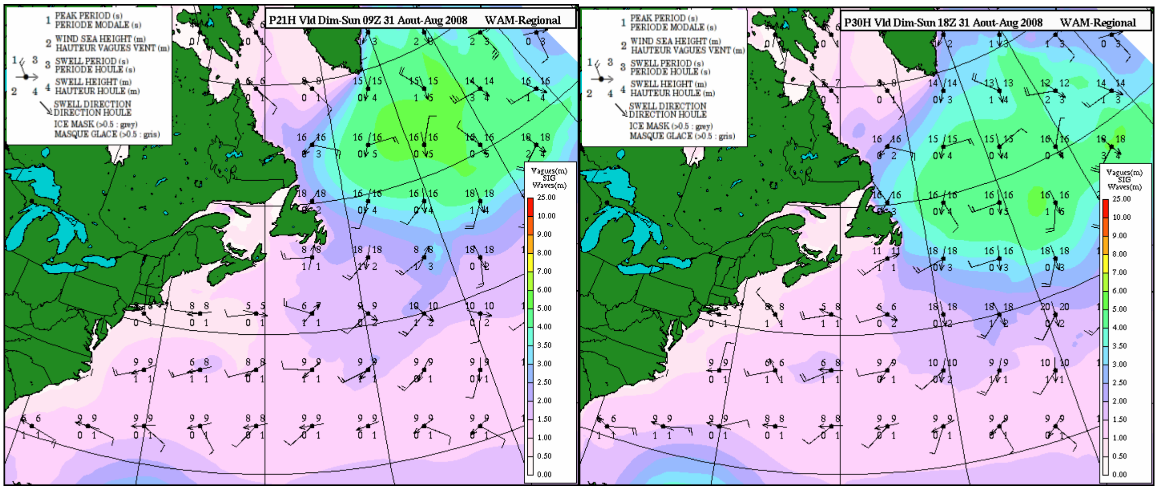


Figure 22. WAM Sea state forecast from the 12Z run on 2008-08-30 (CMC 2008)

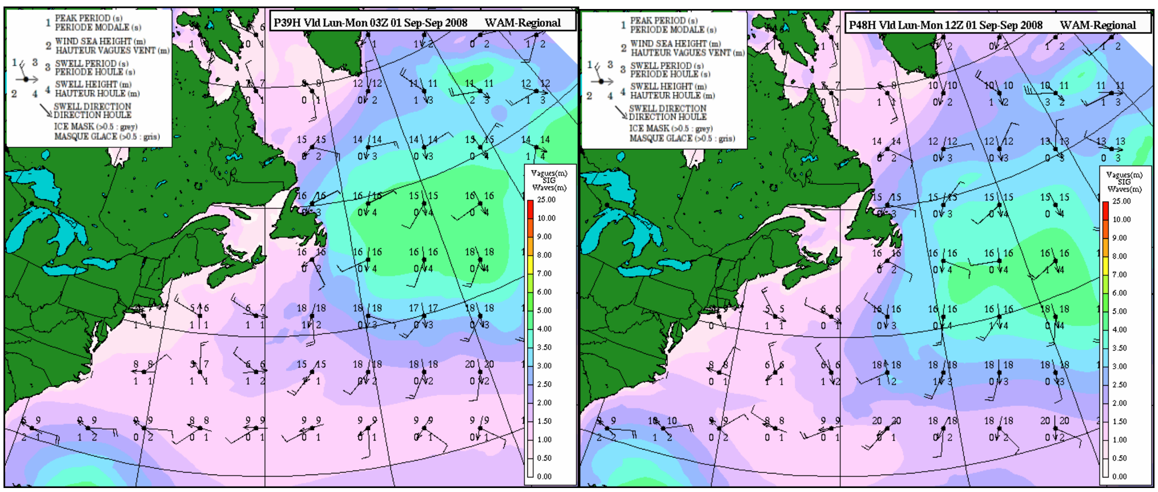


Figure 23. WAM Sea state forecast from the 12Z run on 2008-08-30 (CMC 2008)

The significant wave height forecast produced by both the NWP guidance and the reanalysis yielded similar a forecast. Buoy data from two oil rigs, Terra Nova and SeaRose, located at 46.5 N 48.5 W (Fig 24) was then used to verify the reanalysis and NWP guidance (Fig 25).

The NWP guidance did have a ~+50 cm bias over the average significant wave height measured at the two stations over the duration of the event. The observed significant wave height began to subside at around 0600Z on Monday, September 1, 2008.

Observed Significant Wave Heights

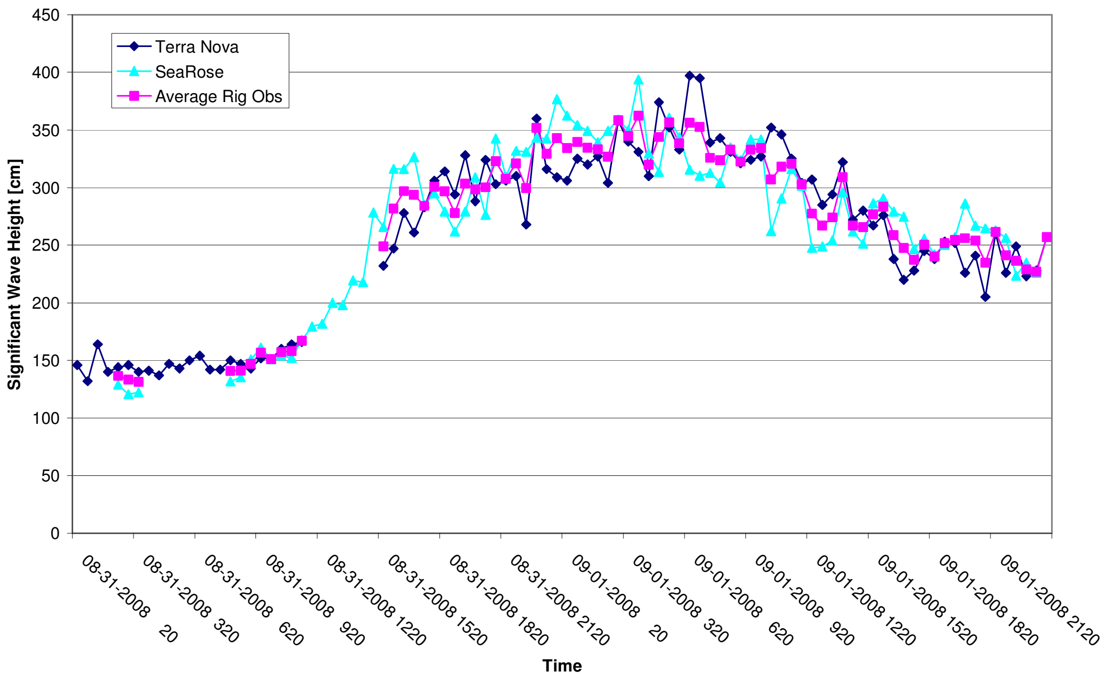


Figure 24. Observed significant wave height

Observed Significant Wave Height from the Terra Nova and SeaRose Buoys and WAM output

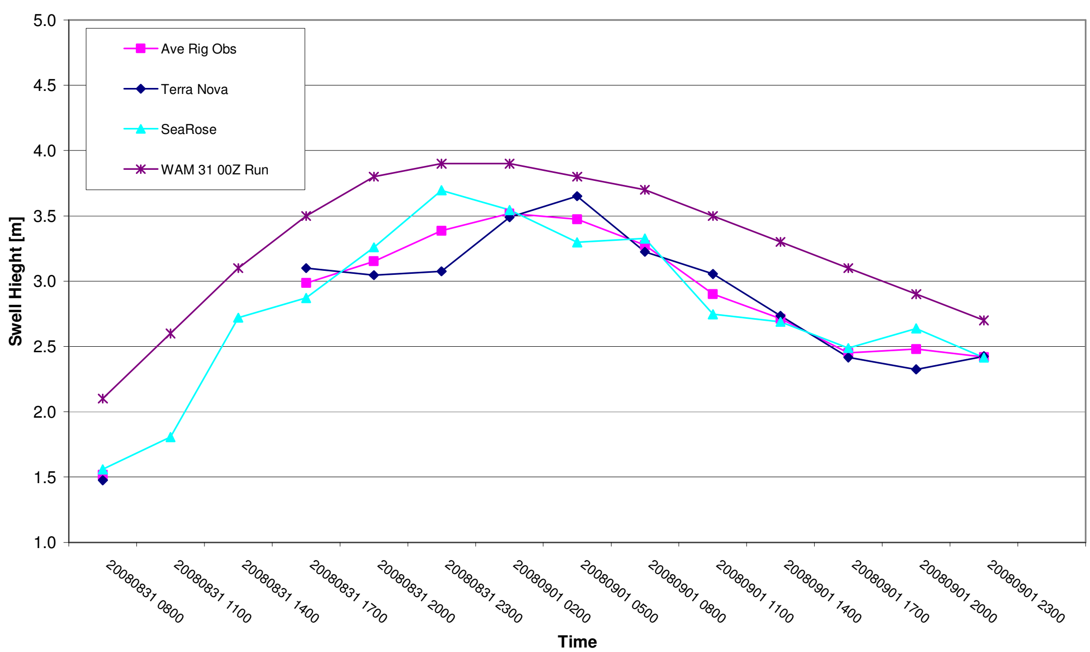


Figure 25. Verification of significant wave heights WAM output.

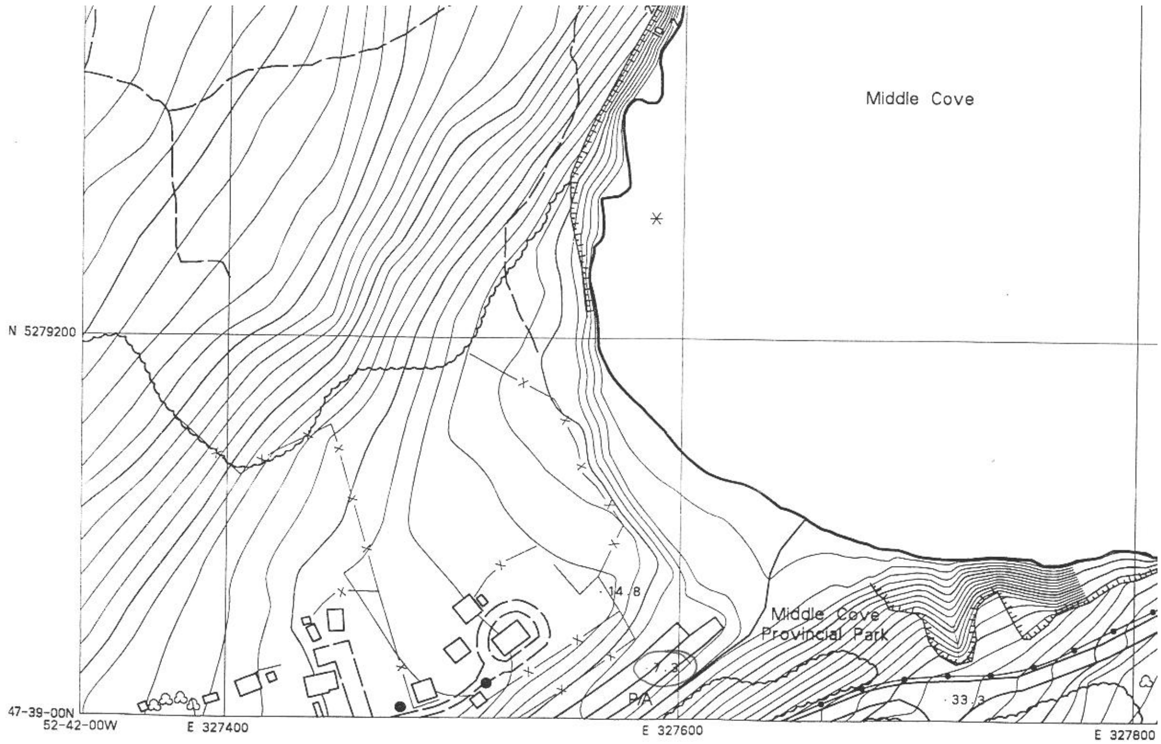
3.3 Site Survey of Middle Cove Beach

Middle Cove Beach is located ~10 km north of the city of St. John's, Newfoundland and faces northeast. Its rugged and scenic U–shaped bay surrounded by a steep cliff make it popular among tourists and residents in the summer. The beach is composed of gravel and sand with the largest clast sizes distributed half way up the beach creating a berm dividing the foreshore from the backshore and denoting the high tide mark. The parking lot is found at the south end of the beach at an elevation of 7.3 m above the mean sea level, which for this site is 60 cm above the lowest low mean water level (see Figs 26-29).

Figure 26. Looking NE from the parking lot

Figure 27. Looking N from a hill on the east side of the breach

Figure 28. Looking N from the east side of the beach



1N10 - 422

Figure 29. Topographic map of Middle Cove Provincial Park,
Surveying and Map Division with the Newfoundland and Labrador Provincial government

3.4 Shoaling Reanalysis

On the afternoon of Sunday, August 31, 2008, a northeast swell with a significant wave height of ~3.5 m and a period of 16 seconds began to transition from a deep water wave to a shallow water wave in ~200 m of water approximately 126 km northeast of Middle Cove Beach. The wave then became a pure shallow water wave in a depth of ~20 m approximately 680 m northeast of Middle Cove Beach (Figs 30 - 34).

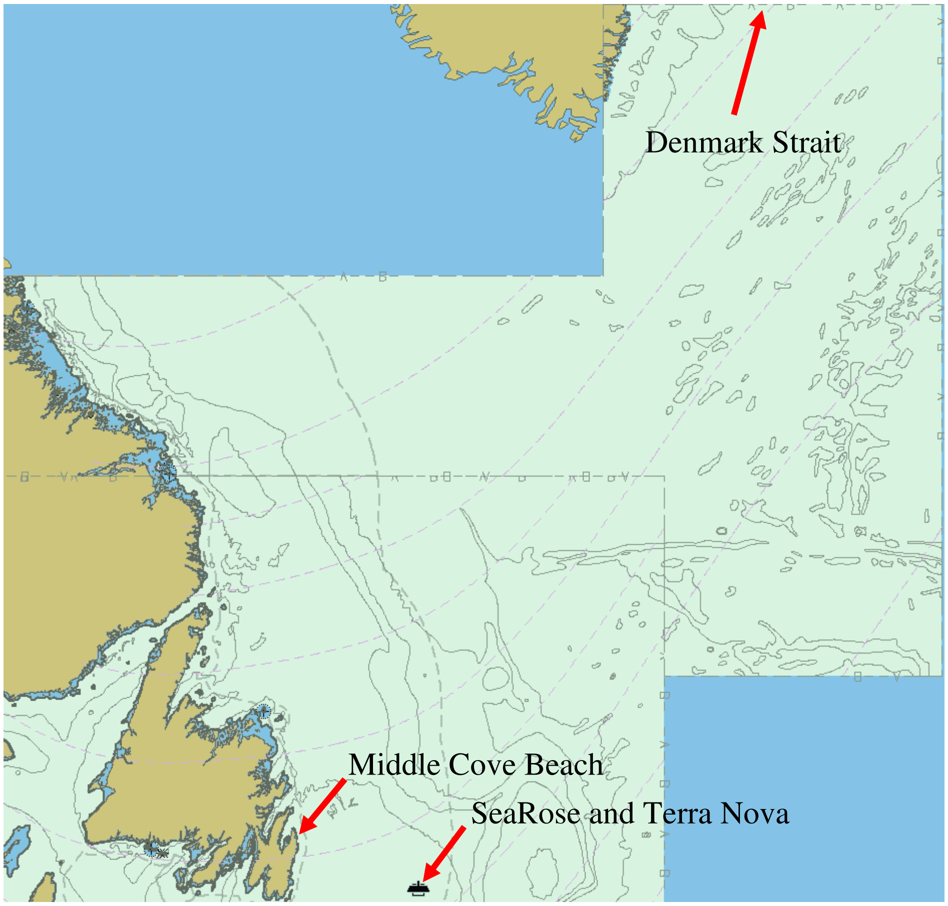


Figure 30. Bathymetry of the North Atlantic.

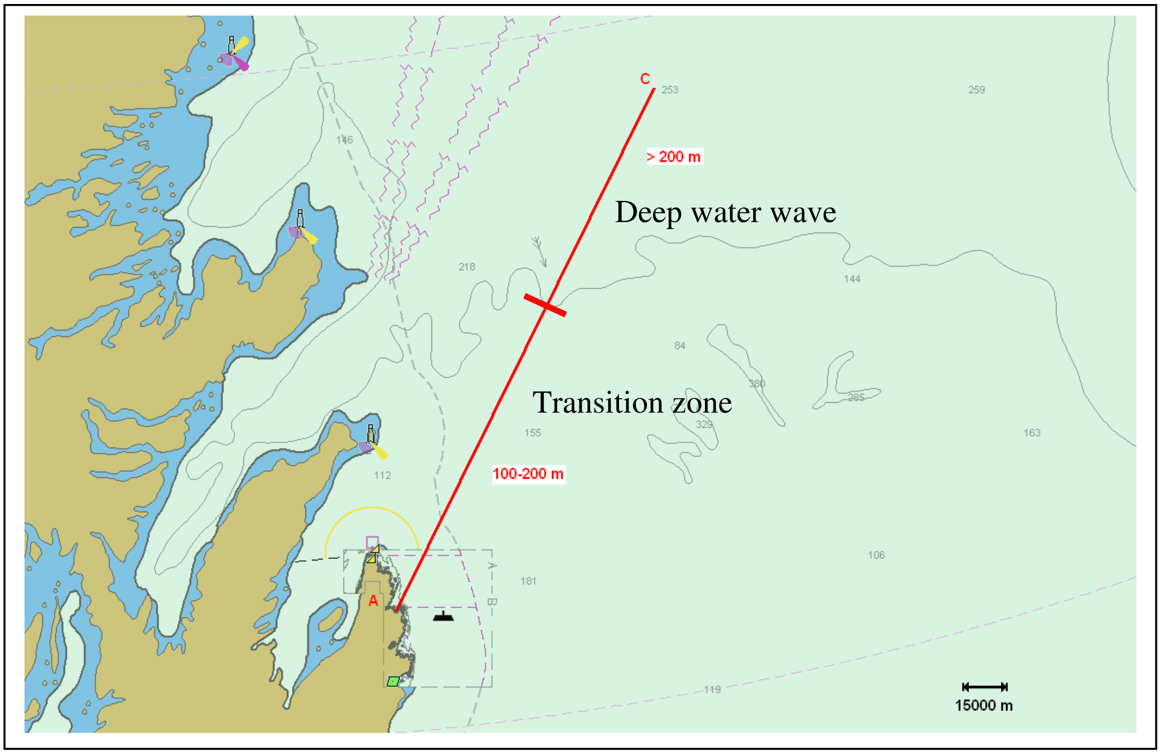


Figure 31. Bathymetry of the northern half of the east coast.

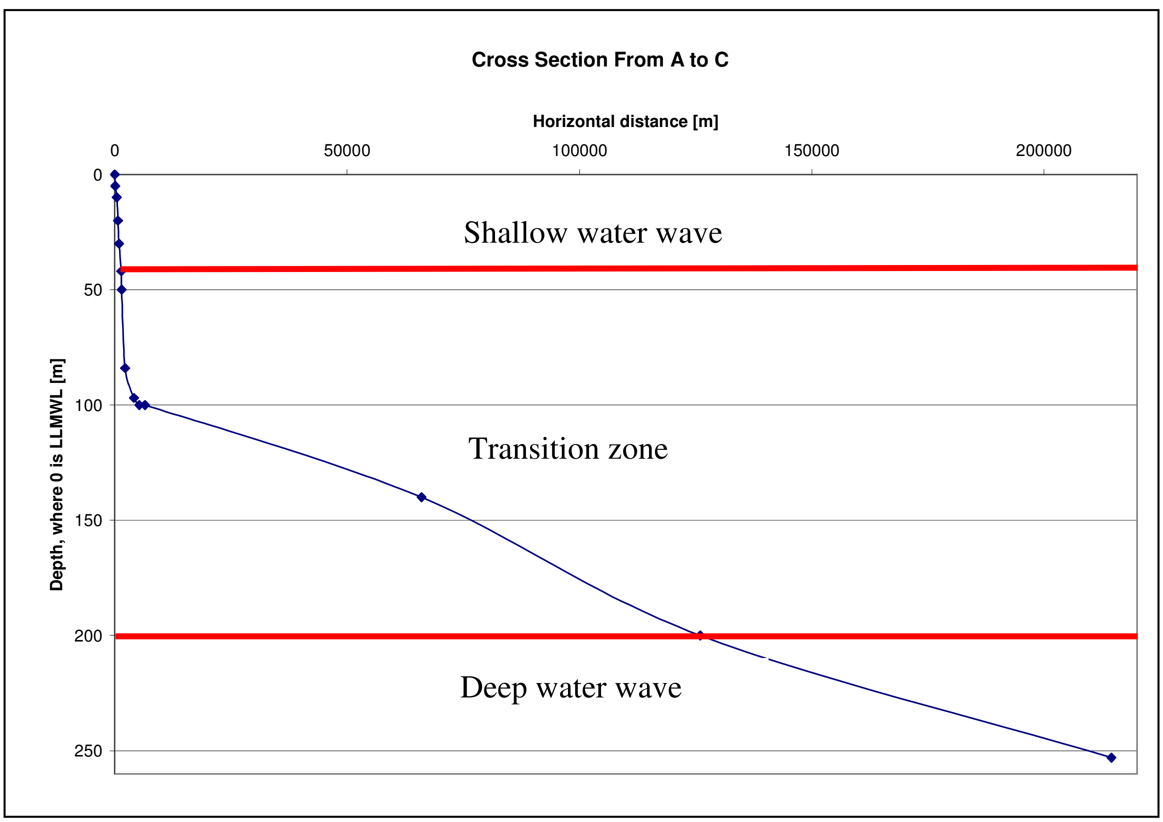


Figure 32. Cross section of water depth from Middle Cove beach to a point 215 km to the Northeast.

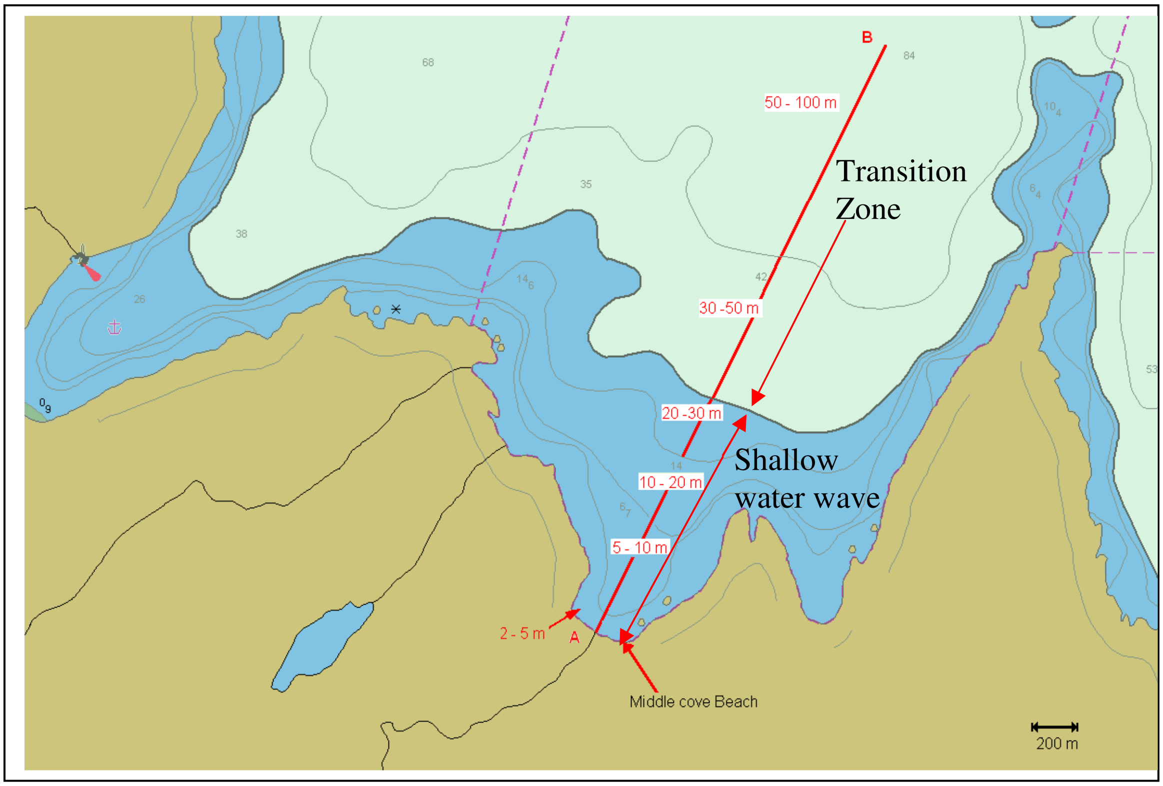


Figure 33. Bathymetry of the near shore region of Middle Cove Beach.

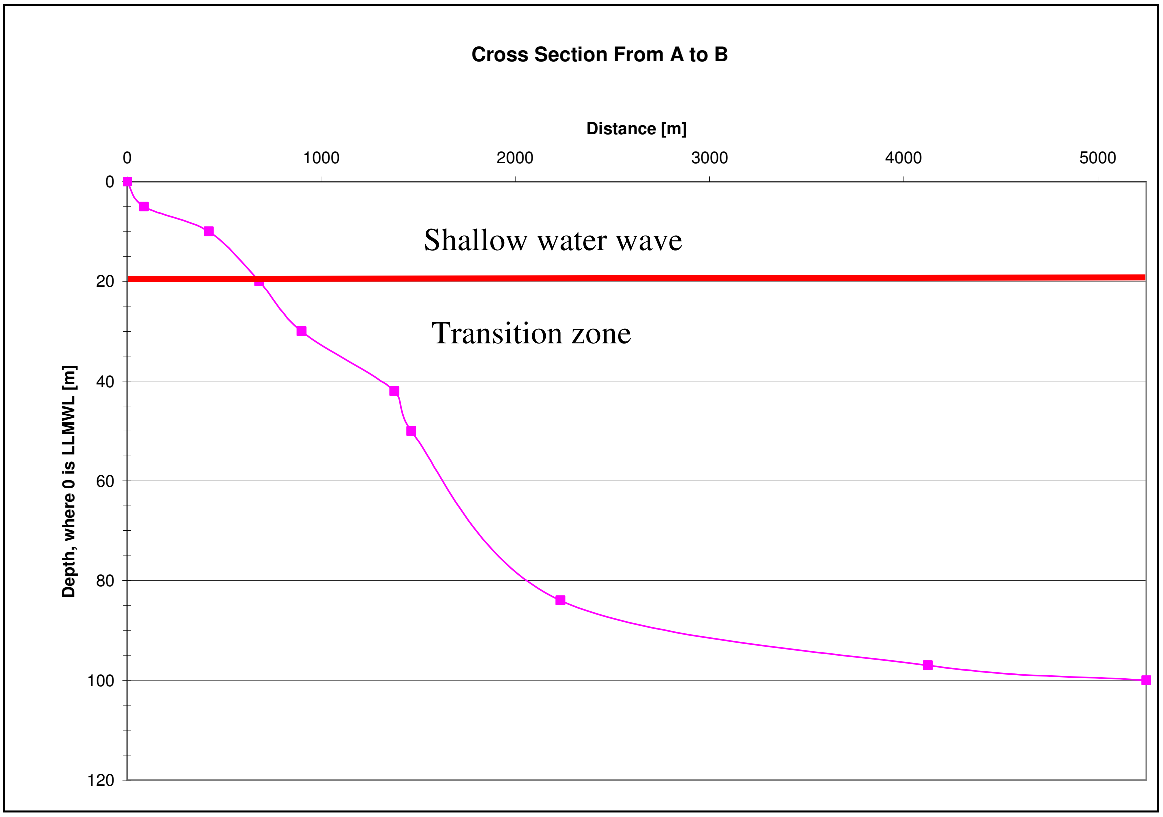


Figure 34. Cross section of water depth from Middle Cove beach to a point 5.25 km to the Northeast.

Upon examining the bathymetry surrounding Middle Cove Beach three distinct slopes are observed (Fig 35). Section A lies closest to the shore and extents to a depth of 5 m below the lowest low mean water level and has a 1:18 slope. Section B lies at depth between 5 and 10 m below the lowest low mean water level and has a 1:67 slope. Section C lies at a depth less than 20 m below the lowest low mean water level with a 1:24 slope. However, local features such as rock reefs as well as long shore bars and troughs that change in size and location daily and seasonally will affect the slope of the sea bed and are not resolved due to the resolution of the bathymetry charts. If the bottom slope was estimated from a depth of 30 m to lowest low mean water level (LLMWL), this bottom slope, D, would have a 1:30 slope. Additionally, along the same cross section of beach the foreshore slope was estimated to have a 1:7.3 slope.

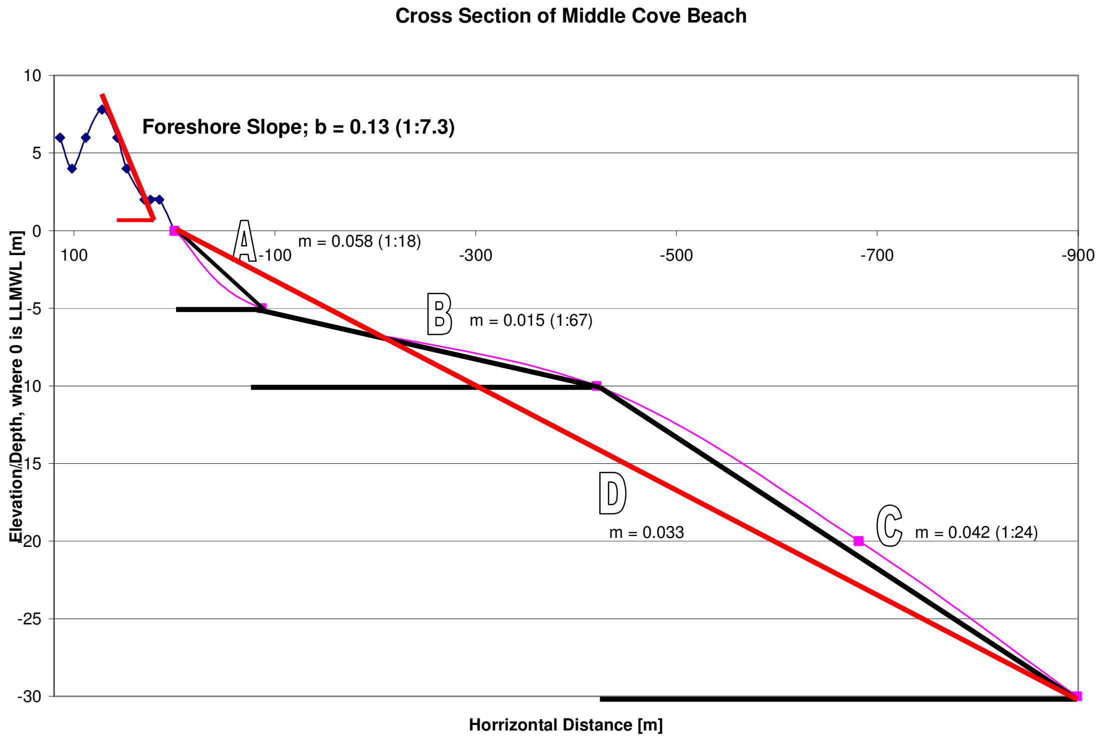


Figure 35. Cross section of bathymetry and topography from Middle Cove beach from the parking lot into the cove along the same line as in figure 33.

From the accounts of the witnesses, it is apparent that during the afternoon large waves caught beach-goers off guard and by the evening of Sunday, August 31, 2008 the wave set-up from the shoaling waves caused the water level to an elevation where the resulting wave run up reached to the base of the parking lot. By the time the waves had moved into the cove, they were totally shallow water waves having a significant momentum transport through the water column. The cove narrow as the depth decreased towards the beach would cause the inward flow of water to amplify, especially when considering the long wave lengths of the incident swell approaching from deep water.

4 survive rogue wave at Middle Cove Beach, N.L.
Last Updated: Tuesday, September 2, 2008 | 1:25 PM NT
CBC News

Four people were rescued after a rogue wave swept them into the ocean outside St. John's on Sunday evening.
Several families were on Middle Cove Beach enjoying the late-summer evening when two large waves struck the waterfront, reaching 20 metres inland to the parking lot.
One witness said several dozen people were enjoying a bonfire on the beach when the giant wave came out of nowhere and rolled them over.
Two adults and two children were carried out to sea and several more were knocked off their feet.

People ran for higher ground and strangers helped keep each other from being carried out to sea, said Randy Hammond, a superintendent with the St. John's Fire Department.
"They took the initiative to go into the water to recover [them] — in one case, a mother went out after her seven- or eight-year-old son, who was washed out," he said.
None of them suffered serious injuries.
Glenda Antle, who was knocked down by the wave, said she was lucky to have help close by.
"This big wave just grabbed me and washed me out, and when it subsided some, my husband and a stranger, who I'd like to thank, grabbed me, and got me … out of it," said the St. John's resident.
Rescue officials said everyone who was on the beach was found.

Susan Hann-Haley was at Middle Cove beach that day and recounts the events that occurred that afternoon;

"I never turn my back on the ocean and I could predict to a certain extent the size of the waves by watching the waves break on the side of the cove. It gave me a heads up as to what was about to hit the beach. It was a single wave I believe. Can't say for certain, I think it was a breaker. I was too pre-occupied with Gavin's safety.

I knew a big one was going to hit because I had been watching the side of the cove, left side if you're facing the water. So I just picked up Gavin and waited, it came up the beach pretty quick. I got soaked and our things got washed away. We were seated a ways back from the where I could see where the beach was still wet from previous waves/tides.

That was mid afternoon. I left right after that. I wasn't there when those 4 people got swept out. I think that was about 4 hours later."

4. Results

Wave height observations from both the Terra Nova and SeaRose buoys did show individual waves that where twice the size of the significant wave height for the observation period. However, even in the absence of these waves one would expect the set-up from the significant waves to be a threat in this situation.

The following time series were created using the local bathymetry, H_s and T observed at the SeaRose located ~340 km to the eastsoutheast of Middle Cove Beach, and sea level observed at the tide gage in St. John's Harbour. The sea level and significant wave heights and peak periods at Middle Cove Beach where assumed to be similar to St. John's and the Sea Rose respectively.

4.1 Wave Set-up Results

Equations 4 through 9, H_s and T measured at the SeaRose and the bottom slopes calculated from figure 34 where used to calculate H_B (Fig 36) and d_B (Figure 37) at Middle Cove Beach during the event.

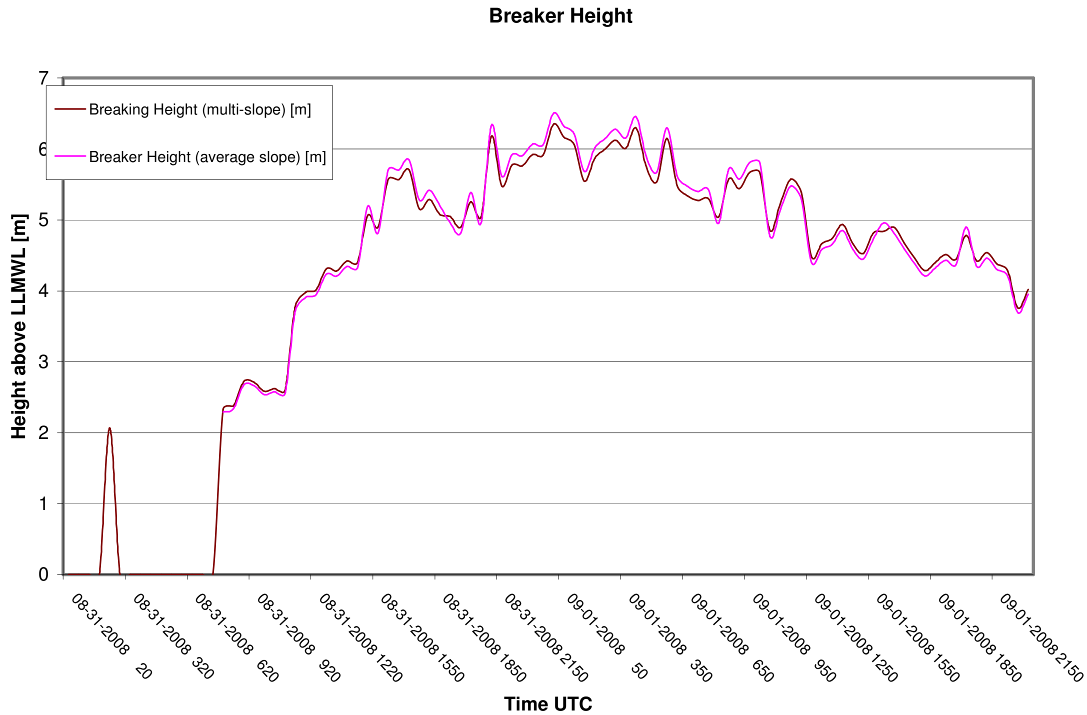


Figure 36. Resulting breaking wave heights over different bathymetric resolutions.

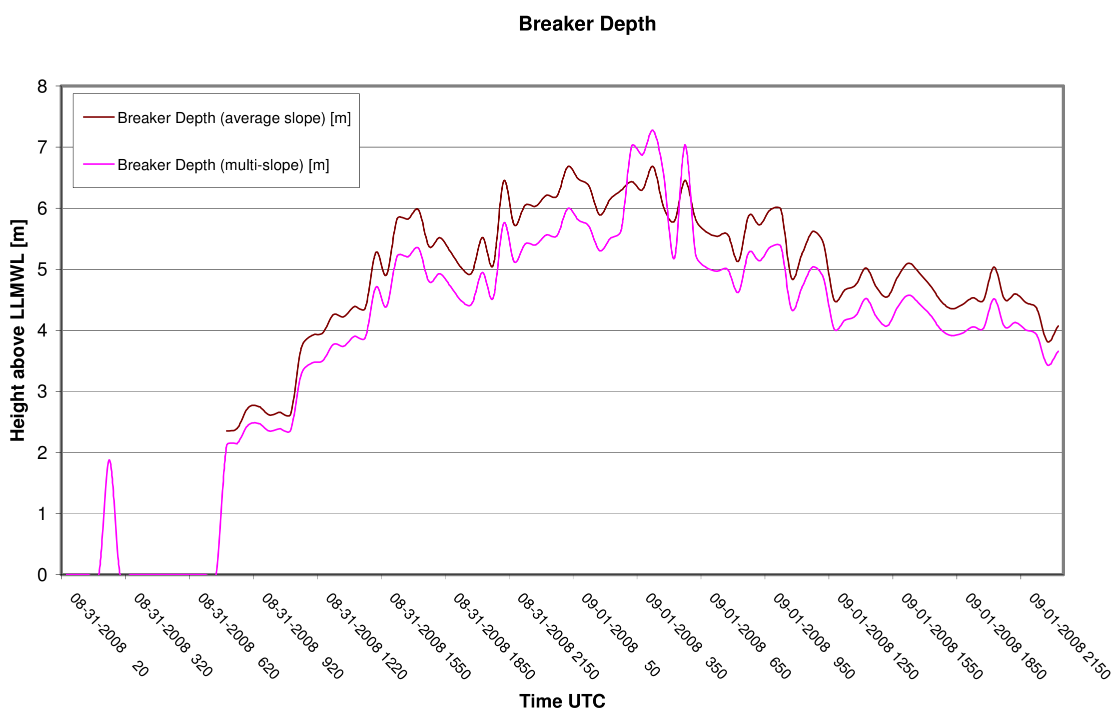


Figure 37. Resulting breaker depth over different bathymetric resolutions.

In investigating the sensitivity to H_B and d_B in an averaged sloped and multi-sloped bathymetric cases at Middle Cove Beach it appears that varying the resolution of the bathymetry only perturbed H_B and d_B by about 2% (Figs 36 and 37). I was noted while examining the multi-sloped bathymetric case that when the breaking depth was greater then 5 m, the wave would have broken over the less steep section B. This caused a decrease in H_B with respect to it breaking over the steeper section A or the averaged bathymetry D. This result was further illustrated when wave set-up is calculated as a percentage of H_B (Fig 38).

The multi-slope example oscillated around the averaged slope when calculating wave set-up using the Goda method, therefore it is reasonable to estimate the maximum wave set-up, from the four methods used, as the Goda method over the averaged slope. It is also apparent that the minimum value of wave set-up as a percentage of H_B is the lower boundary of the method introduced in the COMET module, Shoaling Waves, (2006).

A time series of the resulting maximum, mean and minimum wave set-up at Middle Cove Beach was then plotted to illustrate the spread in water level rise depending on the method used (Fig 39).

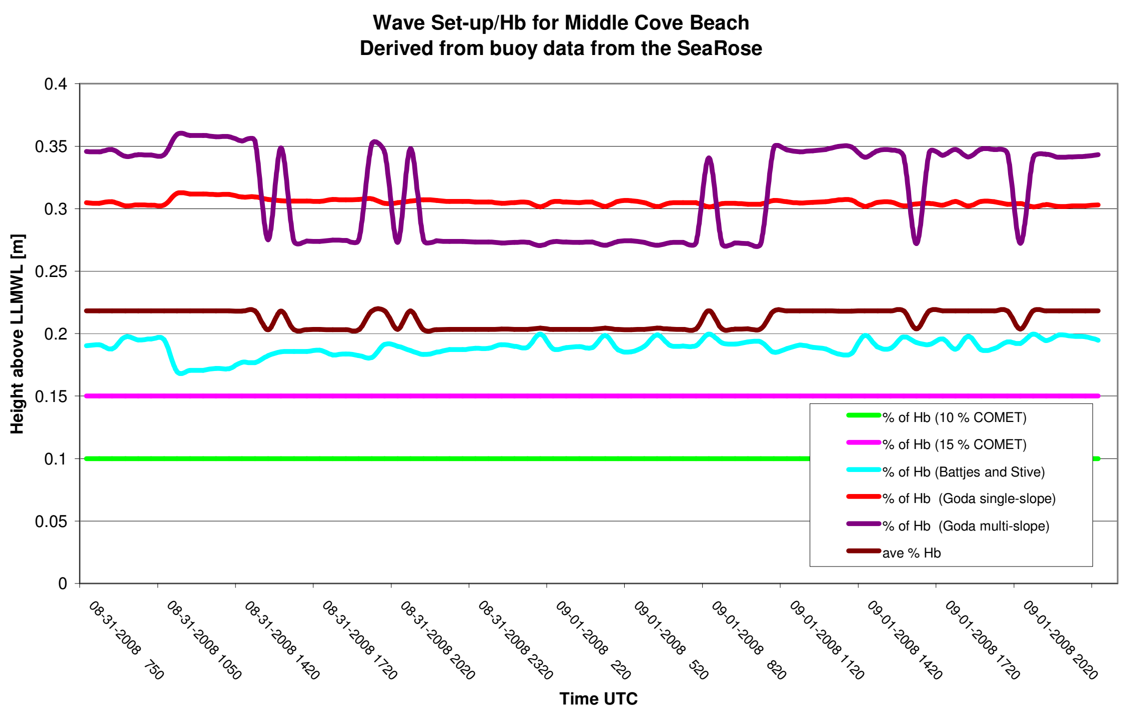


Figure 38. Resulting wave-up as a percent of breaking wave height.

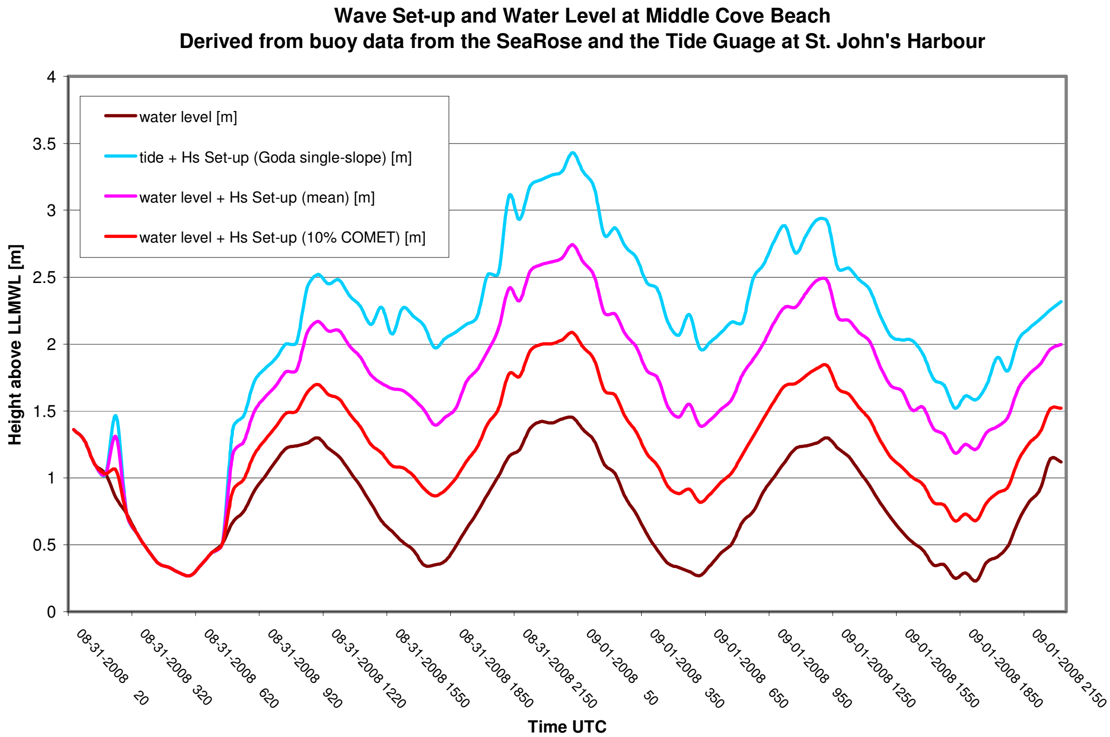
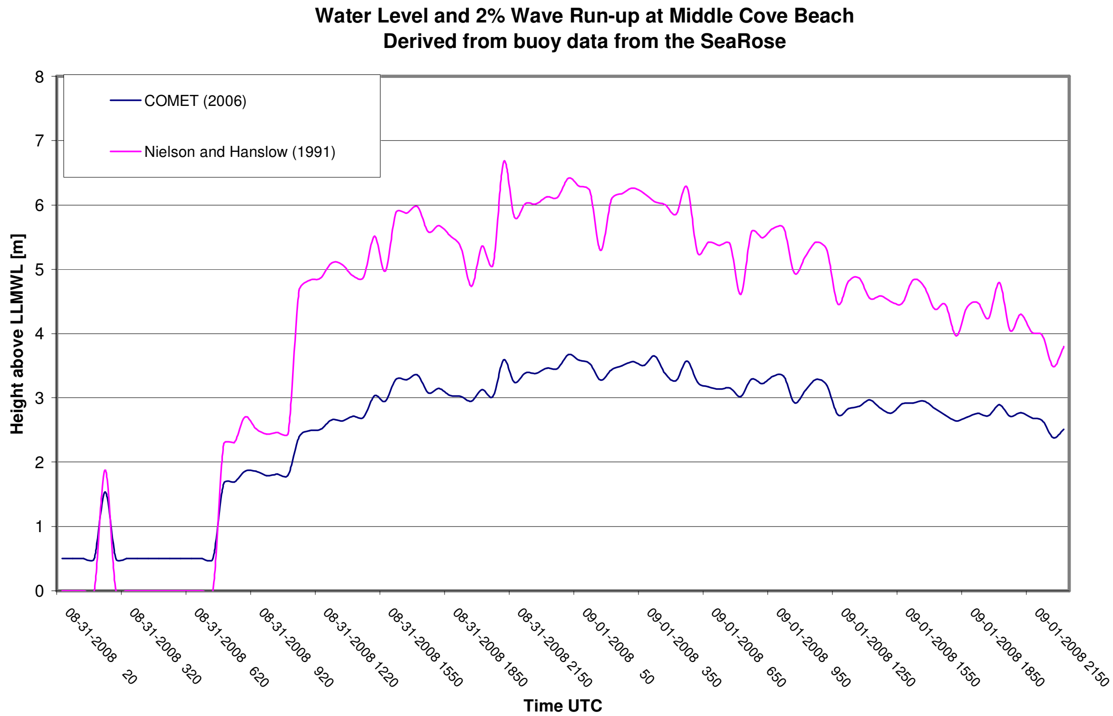


Figure 39.

4.2 Wave Run-up Results

A comparison of the two methods of calculating wave run-up was then calculated using the same method as stated in the previous section to generate a time series (Fig 40). It is evident that there is a significant difference in the calculated wave run-up between the two methods with the Nielson method increasing to about 3 m larger then that of the COMET method during the peak of the event.

These two methods were then added to the maximum, mean and minimum combined sea level elevation due to the tide and wave set-up (Fig 41). It is evident from figure 40 that the combined sea level rise is more sensitive to the method of calculating wave run-up then from the method of wave set-up. Additionally, for this simplified one dimensional study, when comparing these methods against the witness's accounts of the event it is apparent that the Nielson method would resolve this event better.



Water Level and 2% Wave Run-up at Middle Cove Beach
Derived from buoy data from the SeaRose
COMET (2006)
Nielson and Hanslow (1991)
Height above LLMWL [m]
0
1
2
3
4
5
6
7
8
08-31-2008 20
08-31-2008 320
08-31-2008 620
08-31-2008 920
08-31-2008 1220
08-31-2008 1550
08-31-2008 1850
08-31-2008 2150
09-01-2008 50
09-01-2008 350
09-01-2008 650
09-01-2008 950
09-01-2008 1250
09-01-2008 1550
09-01-2008 1850
09-01-2008 2150
Time UTC

Figure 40.

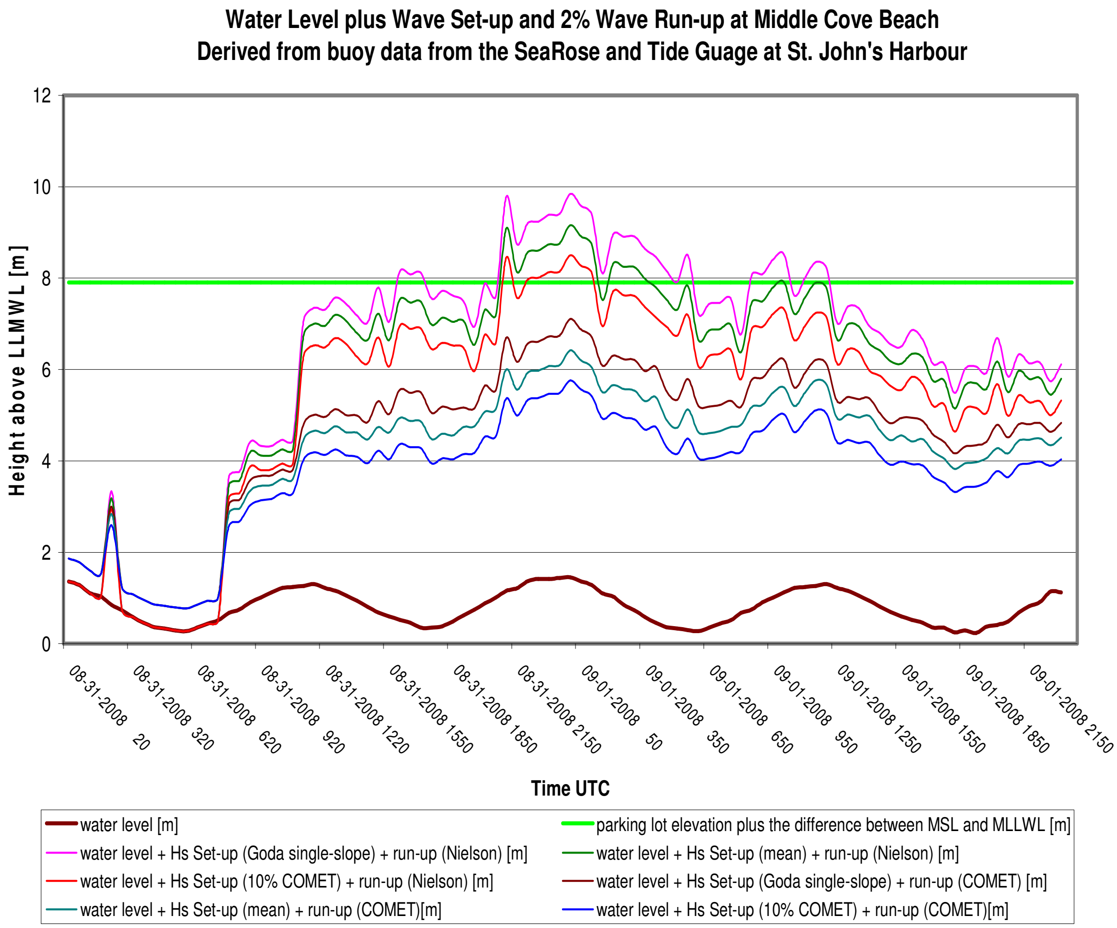


Figure 41.

4.3 Nomogram

From this one event it difficult to determine what the more accurate method of calculating wave set-up would be. In order to attempt to develop a nomogram to aid the forecaster in better identifying a similar event the mean wave set-up will be used but a 10% uncertainty surrounding this calculation is stressed.

(13) Estimated wave set-up = $0.21 * H_B \left({}^{+}\!/\!_{-} 10\% \right)$

However, all stated in the previous section, the Neilson method of calculating wave run-up will be used with more confidence.

Combining equations 4, 12 and 13, an equation for combined sea level rise due to wave run-up, wave set-up and water level at Middle Cove Beach can be attained that is a function of deep water H_s, T and near shore and foreshore slopes.

(14) $$\text{wave run-up} = 0.21 * H_s * \left[.575 m^{0.031} \left(\frac{H_s}{1.56 * T^2} \right)^{-0.254} \right] + 1.19 * b * \left(H_s * 1.56 * T^2 \right)^{1/2} + water\_level$$

Using the height of the parking lot, 7.9 m above the LLMWL, as a proposed warning criterion for height of the wave run-up to reach, equation 14 can be re-written to solve iteratively for H_s as a function of T and water level (Fig 42).

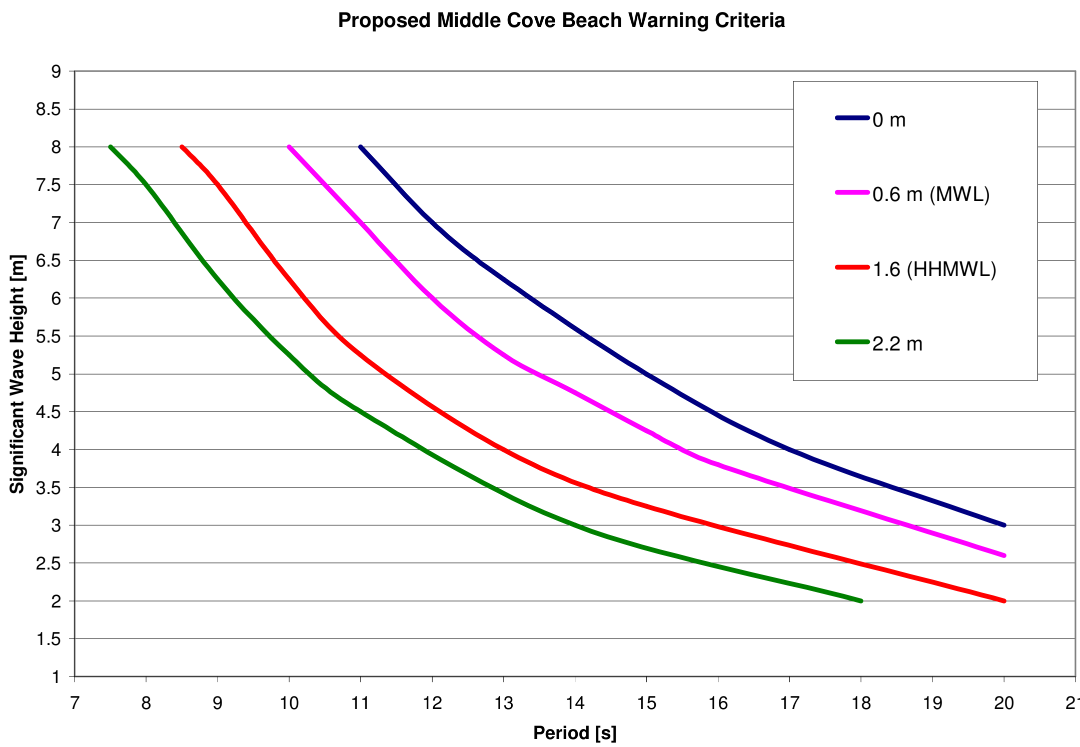


Figure 42.

For a northeasterly swell, the perturbed sea level at Middle Cove Beach could then be estimated by the deepwater wave height and period and local sea level elevation. For a forecasted northeasterly swell over the northern half of the East Coast a forecaster could determine the coastal hazard at Middle Cove Beach using this nomogram in figure 42. For example, a northeasterly swell with 4 m significant wave height and a 13 second period coinciding with a 0.6 m water level would not pose a significant coastal hazard under normal circumstances. However, if the period of the swell was increased to 16 seconds, one would expect set-up from the shoaling waves to reach the base of the parking lot at Middle Cove Beach and cause a hazard to beach-goers.

5. Conclusion

With the knowledge of this synoptic event and with the use of the nomogram perhaps similar situations may be accurately forecasted and appropriate action may be taken to inform the public.

This study is only based on one case, with one event occurring, but it is a first step of many in hopes of a more in-depth study of this event with the use of a shallow wave model, such a SWAN may glean more insight. This study also raises additional questions that may be worth further investigation. What is the frequency for a similar event to occur at Middle Cove Beach? Are there other popular beaches in Newfoundland that are at risk and what would their warning criteria be?

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