Contributing to the Prediction of Coastal Flooding:
Simulating Wave Heights and Directions along the Coast of
Barrow, Alaska

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ABSTRACT

The community of Barrow, Alaska, Alaska has experienced coastal flooding during extreme weather events throughout events in the past 60 years. To improve the predictions of coastal flooding in coastal communities worldwide, models have been used to simulate flooding caused by storm surges. In many cases the coastal flood heights simulated by these coastal flooding models have been less than the flood heights that have been observed by the affected communities. The hypothesis for this project is that the results from coastal flooding models would be closer to observations if the contributions of waves to local sea level rise were taken into account. The Simulating Waves Nearshore (SWAN) model was used to simulate wave heights and directions offshore and in the Barrow coastal vicinity. Wind conditions from 11 historical storms and a recent storm (July 2003) were used as input data for SWAN. The wave simulations for the 11 historical storms showed wave development as a response to a constant wind speed and direction. The wave simulations for the July 2003 storm showed wave development as a response to the average wind speeds and directions every 6 hours. The output data for all the wave simulations consisted of wave height and direction distributions offshore and in the Barrow coastal vicinity. The resulting wave height data compared quite well to community recollections of the coastal wave heights. In a future application, these wave heights will be incorporated into coastal flooding models to test the contribution of waves to coastal flooding in Barrow.

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INTRODUCTION

The simulation of wave heights and direction along the Barrow coastline will be used in the assessment of the total coastal flooding that has occurred during late summer and fall storms in Barrow, on the North Slope of Alaska. A state-of-the-art wave simulation model, Simulating Waves Nearshore (SWAN), was used to generate wave heights and directions over a 2-dimensional grid surface representing the southern Chukchi and Beaufort Sea, which are bounded by the Alaska North Slope coastal region. With these wave simulations, a total coastal flood height can be simulated incorporating wave heights and directions with models that use storm surges to simulate coastal flooding.

Barrow, Alaska, is an Arctic coastal community vulnerable to the impacts of coastal flooding. The community is situated on the western face of Point Barrow, the most northern location on the Alaskan North Slope, and the meeting point of the Chukchi and Beaufort Seas. This region of Alaska consists of a low elevation tundra wetlands with relatively flat terrain. The community’s average elevation is less than 10 meters above sea level (Lynch et al. 2003:3). Barrow is not located within any harbors or inlets. The community sits on an unprotected coastline facing out towards the Chukchi Sea. The Chukchi coastal area near Barrow is an area of open water with no local barrier islands and a narrow continental shelf (Lynch et al. 2003:719).

The worst flooding in Barrow’s recent history described by Lynch et al. (2003) took place during a rare cyclonic storm 3-5 October 3-5, 1963. The maximum storm surge height was estimated to be 3 m. The estimated maximum wave height was an additional 3 m. Nineteen buildings were destroyed, and the local drinking water was contaminated by the flow of saltwater into the lagoon that contains the community’s water supply. The cost from the storm amounted to $3.25 million, which would have cost over $19 million had the storm occurred in 2002 (pp. 5).

Most of Barrow’s permanent residents are indigenous Inupiat, and about half live a subsistence lifestyle, making access to the coast critical for hunting, whaling, and fishing (Lynch et al. 2003:3). The Inupiat and other Barrow residents are concerned about an increased risk of coastal flooding in their community due to recent observed changes in the local climate such as earlier spring thaws and a longer ice-free season (Lynch et al. 2003:3). There are no tide gauges or buoys near shore to measure sea level rise, wave heights, and wave directions in the Barrow coastal vicinity. There is little data to assess the maximum potential wave heights or the maximum potential coastal flood height that can occur in the Barrow coastal vicinity. It is therefore important to understand the processes that contribute to coastal flooding in Barrow to assess the current risk and to anticipate which areas of the community are the most vulnerable to coastal flooding.

Wave set-up is the contributing factor that waves make to coastal flooding. Coastal flooding is caused when breaking waves on the shore pile up over each other and increase the water level over the shore (McInnes et al. 2002:4). Since there are no measurements of wave heights in the Barrow coastal vicinity, the maximum potential
wave set-up height is not known. Knowledge of the maximum potential wave set-up flood height would improve simulations of coastal flooding.

Wave height in the open ocean is a function of the wind speed, the fetch (the time duration of a particular wind speed in the same direction over an area of open water), and the bathymetry (depth and terrain of the sea floor) (McInnes et al. 2002:4). The wave set-up is related to the open ocean wave heights. These open ocean waves eventually move into the coastal vicinity and break along the shoreline. The amount of wave set-up along the shore is dependant on the wave height and direction the waves (McInnes et al. 2002:4). Wave height relates to the amount of energy a wave has and this energy decreases as the wave approaches the shore (Thurman 1985:216). The wave slows down due to the bottom friction drag of the shallow water, and its height briefly increases before it breaks on the shore. Wave set-up increases when the wave approaches the shore head-on.

This research required a wave simulation model that could be used to depict wave heights offshore and in the Barrow coastal vicinity. SWAN is an advanced 3rd generation wave simulation model that has been designed to simulate wave height and direction (Sclavo and Cavaleri 2000:315). In the past, 1st and 2nd generation wave simulation models generated waves based on observations of open ocean wave heights (Booij et al. 1999:7650). The 3rd generation models permit the simulation of waves in the open ocean and in coastal areas by using wind speed and direction as a forcing mechanism. These models also generate wave growth and dissipation in the open ocean and near the shore by adding the effects of quadruplet wave-wave interactions, white capping, and bottom dissipation. Quadruplet wave-wave interactions are waves encountering other waves approaching from four directions in the open ocean. White capping is a wave breaking in the open ocean, and bottom dissipation is the sea floor friction reducing the waves energy and speed as it approaches the coast (Booij et al. 1999:7650). A 3rd generation wave simulation model that has been recently used to generate waves offshore and in coastal areas is the Wave Model (WAM). SWAN incorporates all the effects used by the 3rd generational models, such as WAM, to generate waves for coastal areas. SWAN is an improved 3rd generation wave simulation model because it added features based on the knowledge of general wave conditions near the coast. To improve the accuracy in generating waves in a coastal area, SWAN adds the effects of triad wave-wave interactions (waves encountering other waves from three directions in coastal areas with no wave-wave interaction from a 4th direction due to the coastline), and depth-induced wave breaking on the shore (Booij et al. 1999:7650).

**METHOD**

**Bathymetry**

The bathymetry grid used for SWAN covers an area 390 by 390 km of the Alaska North Slope coastal region, including Point Barrow, and the southern Chukchi/Beaufort Sea. There are a total of 6084 grid points (78 for the east/west x-axis and 78 for the north/south y-axis) spaced evenly every 5 km. Land surface grid points represent areas of “no data” to confine wave simulation to the sea surface grid points. A sea floor depth
is assigned to each grid point located over the sea surface. The sea floor bathymetry depth interval is 50 m. This means each assigned depth to the grid point’s increments every 50 m. An example of this interval would be a grid point with a depth of 0 m for the coastline, followed by grid points with depths of 50 m, 100 m, 150 m, etc., located offshore. A digital elevation and seafloor depth map covering the area of the bathymetry grid is shown in Figure 1.

**Figure 1.** Five km resolution bathymetry grid used in SWAN wave simulations.

The bathymetry grid used for SWAN was compiled at the Cooperative Institute for Research in Environmental Science (CIRES), with data from the National Geophysical Data Center (NGDC) ETOPO2 dataset. The ETOPO2 dataset contains global elevation and seafloor depth data. The ETOPO2 seafloor depth data is arranged in a fine resolution grid with a data grid point placed for every 2 minutes of latitude and longitude over the Earth’s surface. This means the grid points are unevenly spaced globally; furthest apart on the Equator and closer together near the North and South Poles.

To create the bathymetry grid with evenly spaced grid points that could be used in SWAN, it was necessary to re-project the ETOPO2 seafloor depth data from geographic coordinates into Universal Transverse Mercator (UTM) coordinates, which measure distance in meters. The UTM global grid divides the Earth surface into 60 north-south zones that are 6° wide in longitude (USGS Eastern Region Geography, 2002). Within each zone there is a degree of distortion to preserve distances (in meters), area, and shape. With the ETOPO2 data re-sampled into UTM coordinates, there was some distortion of
the North Slope coastal region. However, the re-sampling permitted the grid points in the SWAN bathymetry grid to be spaced evenly 5 km apart for computation.

**Sea ice data**

The sea ice input data used for SWAN came from the National Snow & Ice Data Center (NSIDC). This dataset contains monthly averaged and daily total sea ice concentrations from observations by the US Air Force Defense Meteorological Satellites Program (DMSP) Special Sensor Microwave Imager (SSM/I) series F8, F11, and F13 from June 1987 through July 2003.

Pre-1987 sea ice input data came from the NSIDC Arctic Ice Concentration dataset (ARICECON). This dataset contains monthly Arctic sea ice concentrations from 1 January 1901 through 31 August 1995. The sea ice concentration data from available satellite observations and arctic ice climatology were compiled by John Walsh and Bill Chapman at the University of Illinois into a dataset containing monthly average sea ice concentrations.

**Wind data**

The wind data used for SWAN were obtained from the National Weather Service (NWS) office in Barrow. There were two wind datasets used for SWAN. The first dataset consisted of daily average wind conditions (wind speed and direction) for 11 historical storms shown in Table 1. The second dataset consisted hourly wind conditions, which were available every hour from 2 PM 28 July 2003 through 7 AM 30 July (Barrow Standard Time) for a storm that occurred in 2003. The hourly wind conditions are shown in Table 2. All 12 storms occurred during the sea ice-free period from July through October over the North Slope and Chukchi/Beaufort Sea region. The wind speeds are in meters per second (m/s) and the directions are in degrees clockwise with 0° as North, 90° East, 180° South, and 270° west for both wind datasets.
Table 1. List of 11 storms with wind conditions used in the SWAN wave simulations.

<table>
<thead>
<tr>
<th>Storms</th>
<th>Speed</th>
<th>Direction</th>
</tr>
</thead>
<tbody>
<tr>
<td>24-Aug-50</td>
<td>14.7 m/s</td>
<td>68 (East/Northeast)</td>
</tr>
<tr>
<td>29-Sep-59</td>
<td>13.9 m/s</td>
<td>90 (East)</td>
</tr>
<tr>
<td>3-Oct-63</td>
<td>17.4 m/s</td>
<td>270 (West)</td>
</tr>
<tr>
<td>13-Sep-70</td>
<td>10.7 m/s</td>
<td>310 (Northwest)</td>
</tr>
<tr>
<td>11-Oct-77</td>
<td>13.4 m/s</td>
<td>90 (East)</td>
</tr>
<tr>
<td>12-Sep-86</td>
<td>9.8 m/s</td>
<td>225 (Southwest)</td>
</tr>
<tr>
<td>20-Sep-86</td>
<td>13.9 m/s</td>
<td>225 (Southwest)</td>
</tr>
<tr>
<td>29-Jul-93</td>
<td>12.5 m/s</td>
<td>270 (West)</td>
</tr>
<tr>
<td>11-Oct-93</td>
<td>15.6 m/s</td>
<td>270 (West)</td>
</tr>
<tr>
<td>24-Oct-98</td>
<td>17.0 m/s</td>
<td>70 (East/Northeast)</td>
</tr>
<tr>
<td>10-Aug-00</td>
<td>16.5 m/s</td>
<td>270 (West)</td>
</tr>
</tbody>
</table>

Table 2. List of 6-hourly average wind conditions for the July 2003 storm.

<table>
<thead>
<tr>
<th>Times</th>
<th>Speed</th>
<th>Direction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Monday 28 July 7 PM</td>
<td>7.8 m/s</td>
<td>225 (Southwest)</td>
</tr>
<tr>
<td>Tuesday 29 July 1 AM</td>
<td>10.3 m/s</td>
<td>211 (South/Southwest)</td>
</tr>
<tr>
<td>Tuesday 29 July 7 AM</td>
<td>15.0 m/s</td>
<td>251 (West/Southwest)</td>
</tr>
<tr>
<td>Tuesday 29 July 1 PM</td>
<td>16.5 m/s</td>
<td>270 (West)</td>
</tr>
<tr>
<td>Tuesday 29 July 7 PM</td>
<td>13.7 m/s</td>
<td>285 (West/Northwest)</td>
</tr>
<tr>
<td>Wednesday 30 July 1 AM</td>
<td>9.5 m/s</td>
<td>274 (West)</td>
</tr>
<tr>
<td>Wednesday 30 July 7 AM</td>
<td>9.1 m/s</td>
<td>289 (West/Northwest)</td>
</tr>
</tbody>
</table>

The model grid

The computational wave simulation grid used in SWAN covered an area 390 by 390 km covering a region including the Chukchi Sea, the western Beaufort Sea, and the coastal North Slope. The SWAN computational grid is was aligned with the bathymetry grid. All grid points within the computational grid are aligned with the grid points of the bathymetry grid for depth induced wave propagation and dissipation. The correct alignment of these two grids is critical for an accurate representation of the wave height and direction that would occur over a given seafloor depth. The boundaries of wave simulation within the SWAN computational grid were the North Slope coastline and the western, northern, and eastern the edges of the grid.
Wave Simulation

The SWAN wave simulations were run in two parts. The first part was the simulation of waves based on constant wind speeds and directions from 11 historical storms. The second part was the simulation of waves based on wind speeds and directions every 6 hours for the storm that occurred from 28 July 2003 to 30 July 2003. In both parts, SWAN was programmed to simulate wave height and wave direction over the study region.

For each SWAN wave simulation of the 11 historical storms, a sea ice edge was added as a latitudinal boundary based on the areas where the sea ice concentration was 90% greater in the Chukchi and Beaufort Seas. For 6 storms that occurred after 1 June 1987, the daily sea ice concentrations were available. For these 6 SWAN simulations, the sea ice edge was added based on the ice concentration that was present during the day of each storm. For the storms that occurred before June 1987, only the average monthly sea ice concentrations were available. The sea ice edge for these storms was added based on the average ice concentration of the month when a particular storm occurred. After the sea ice edge was added for the storms before and after 1987, a total of 11 waves simulations were run, one for each storm.

No initial boundary conditions were prescribed for these wave simulations. The boundary conditions for the SWAN wave simulations are a prescribed wave height and direction given by the user. For these wave simulations, the wave growth started from calm seas (wave height = 0 and wave direction was “none”) and was a response to a constant wind speed and direction.

For the second group of SWAN wave simulations, no sea ice edge was added because little sea ice was actually present within the region during the July 2003 storm. For this wave simulation, 41 hours of wind data from the storm were divided into 7 time slots. Each time slot had 6 hours of wind data. The wind speeds and directions at the start of each hour were averaged within each of the 7 time slots. This produced average wind conditions every 6 hours starting with 7 PM (2 PM through 7 PM average) 28 July, and ending with 7 AM (2 AM through 7 AM average) 30 July. This was done because wave heights and directions are responses to wind conditions that occur over longer time spans. Observations have shown that it takes a significant amount of time for waves to respond to a given wind condition (Thurman, 1985:220). For the July 2003 storm, 7 SWAN wave simulations were run based on these 6-hourly average wind conditions.

The first wave simulation was run with no initial boundary conditions. The following wave simulations were given boundary conditions based on the wave conditions around the periphery of the SWAN computational grid from the previous wave simulation. For example, the wave simulation for the time period, 1 AM 29 July, was prescribed the boundary conditions of the periphery wave heights and directions from the wave simulation for the previous period, 7 PM 28 July (Table 3). The boundary conditions were added to provide a more realistic view of the pre-existing wave conditions that would be present during the passage of a storm. The final wave simulation was run with the average 6-hour wind conditions by 7 AM 30 July, and with
the initial boundary conditions of the periphery wave conditions for the 1 AM 30 July wave simulation.

RESULTS

SWAN simulated wave heights and directions for 11 historical storms and the July 2003 storm in Barrow. Each output plot displays wave heights and directions in the eastern Chukchi Sea and the extreme western Beaufort Sea. The wave height distribution shows wave growth offshore and wave dissipation near the coast. The wave direction distribution shows the direction of wave propagation. Wave direction plots represent the wave direction, in degrees, clockwise from the north. For example, a wave direction of 270º represents an area where the waves were propagated from the west and were moving east.

Wave heights and directions from 11 storms

Wave heights from the simulations for the 11 storms were mostly a function of the wind speed and direction. Sea ice moderately impaired wave development only when the sea ice edge covered more than 50% of the sea surface grid points over the SWAN computation grid. This scenario occurred in the wave simulation for the 24 August 1950 storm (Figure 1). Two storms with winds less than 11 m/s, 13 September 1970 (Figure 2) and 12 September 1986 (Figure 3), had wave heights 1.4 through 1.8 m offshore and 1.6 through 1.8 m in the Barrow coastal region. The winds of these two storms were from the northwest (13 September 1970) and the southwest (12 September 1986). There were five storms with winds 12 m/s through 15 m/s: 24 August 1950, 29 September 1959, 11 October 1977 (Figure 4), 20 September 1986, and 29 July 1993. The waves simulated for these storms were 2.6 through 3.4 m offshore and 2 through 2.6 m in the Barrow coastal region. Lastly, there were four storms with winds greater than 15 m/s: 3 October 1963 (Figure 5), 11 October 1993, 24 October 1998 (Figure 6), and 10 August 2000. The waves simulated for these storms were 4.2 through 5 m offshore and 3.8 through 4.6 m in the Barrow coastal region.

Wave direction was a direct function of the wind direction. The 13 September 1970 storm had wave propagations from the northwest (Figure 2). Two storms, 12 September 1986 and 20 September 1986, had wave propagations out of the southwest. Four storms, 25 August 1950 (Figure 1), 29 September 1959, 11 October 1977 (Figure 4), and 24 October 1998 (Figure 6), had wave propagation from the east. Four storms, 3 October 1963 (Figure 5), 29 July 1993, 11 October 1993, and 10 August 2000, had wave propagation from the west.
Figure 1. (a) Wave heights (cm) for the 24 August 1950 wave simulation. (b) Wind direction (black arrow) and wave direction (blue arrows) contours (degrees x 10^{-1}) for 24 August 1950 wave simulation.

Figure 2. (a) Wave heights (cm) for the 13 September 1970 wave simulation. (b) Wind direction (black arrow) and wave direction (blue arrows) contours (degrees x 10^{-1}) for the 13 September 1970 wave simulation.
Figure 3. (a) Wave heights (cm) for the 12 September 1986 wave simulation. (b) Wind direction (black arrow) and wave direction (blue arrows) contours (degrees x $10^3$) for 12 September 1986 wave simulation.

Figure 4. (a) Wave heights (cm) for the 11 October 1977 wave simulation. (b) Wind direction (black arrow) and wave direction (blue arrows) contours (degrees x $10^3$) for 11 October 1977 wave simulation.
July 2003 wave heights and directions

Seven simulations of wave height and direction for the 29 July 2003 were performed. The wave heights and the wave directions were functions of the average 6-hour wind speeds and wind directions, and the boundary conditions consisting of wave height and direction from each previous simulation (Table 3). The exception to this was the first wave simulation, for which no boundary conditions were prescribed. The first wave simulation for 7 PM (Alaska Standard Time) 28 July had winds out of the
southwest at 7.8 m/s. The wave heights were 1 m offshore, 0.8 m near Barrow, and the wave propagation was out of the southwest (Figure 7). For the next run, the 1 AM 29 July wave simulation, the wind input was from the southwest at 10.3 m/s. The wave heights were 2 m offshore, 1.6 m near Barrow, and the wave propagation was out of the southwest (Figure 8). The wind input for 7 AM 29 July was from the west at 15 m/s. The wave heights had grown to 4 m offshore and 3.4 m near Barrow, and the wave propagation was still southwesterly (Figure 9). The peak wind input was westerly 16.5 m/s at 1 PM 29 July. The boundary conditions set for this wave simulation with the peak winds were 3.3 m waves from west/southwest (Table 3). The wave heights were 5 m offshore and 4.6 m near Barrow, and propagated from the west (Figure 10). For the following 3 wave simulations, the inputs were decreasing wind speeds and wind directions out of the west/northwest. In the final wave simulation, the offshore wave heights had decreased to 3 m, and the wave heights near Barrow had decreased to 2.6 m (Figure 11). The waves maintained a direction out of the west/northwest (Figure 11).

Table 3. Initial boundary conditions prescribed for each SWAN wave simulation for the 29 July 2003 storm.

<table>
<thead>
<tr>
<th>SWAN wave simulations</th>
<th>Boundary conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Times</strong></td>
<td><strong>Wave height</strong></td>
</tr>
<tr>
<td>Monday 28 July 7 PM</td>
<td>None</td>
</tr>
<tr>
<td>Tuesday 29 July 1 AM</td>
<td>0.8 m</td>
</tr>
<tr>
<td>Tuesday 29 July 7 AM</td>
<td>1.8 m</td>
</tr>
<tr>
<td>Tuesday 29 July 1 PM</td>
<td>3.3 m</td>
</tr>
<tr>
<td>Tuesday 29 July 7 PM</td>
<td>4.0 m</td>
</tr>
<tr>
<td>Wednesday 30 July 1 AM</td>
<td>3.9 m</td>
</tr>
<tr>
<td>Wednesday 30 July 7 AM</td>
<td>3.0 m</td>
</tr>
</tbody>
</table>
Figure 7. (a) Wave heights (cm) for the 28 July 7 PM wave simulation. (b) Wind direction (black arrow) and wave direction (blue arrows) contours (degrees x $10^{-1}$) for 28 July 7 PM wave simulation.

Figure 8. (a) Wave heights (cm) for the 29 July 1 AM wave simulation. (b) Wind direction (black arrow) and wave direction (blue arrows) contours (degrees x $10^{-1}$) for 29 July 1 AM wave simulation.
Figure 9. (a) Wave heights (cm) for the 29 July 7 AM wave simulation. (b) Wind direction (black arrow) and wave direction (blue arrows) contours (degrees x $10^{-1}$) for 29 July 7 AM wave simulation.

Figure 10. (a) Wave heights (cm) for the 29 July 1 PM wave simulation. (b) Wind direction (black arrow) and wave direction (blue arrows) contours (degrees x $10^{-1}$) for 29 July 1 PM wave simulation.
Figure 11. (a) Wave heights (cm) for the 30 July 7 AM wave simulation. (b) Wind direction (black arrow) and wave direction (blue arrows) contours (degrees x $10^{-1}$) for 30 July 7 AM wave simulation.

DISCUSSION

In the SWAN simulations, an extended sea ice edge did not impair wave development as much as was expected. In the wave simulation with the largest extended sea ice edge, the 24 August 1950 storm (Figure 12a), the wave development was only slightly impaired. The winds for this storm were relatively high at 14.7 m/s (33 mph), but the wave heights only reached 3.2 m offshore, and 2.6 m in the Barrow coastal vicinity. Similar wave heights were observed in the wave simulation for the 29 September 1959 storm (Figure 12b). For the 29 September 1959 storm, the offshore wave heights were 3.2 m, the Barrow coastal vicinity wave heights were 2.4 m, the wind speeds were 13.9 m/s (31 mph), and the sea ice edge was far to the north. The 24 August 1950 storm had higher wind speeds, but its heavily extended sea ice edge slightly impaired wave development.
The 3 October 1963 storm also had a large extent of the sea ice-edge, but less than 50% of the sea ice edge covered the sea surface. In the wave simulation for this storm, the wave development was not impaired. High winds of 17.4 m/s (39 mph) generated wave heights of up to 5 m offshore and 4.6 m with the coast. During the actual 3 October 1963 storm the National Weather Service (NWS) in Barrow estimated the wave heights near the shore to be 3 m (Lynch et al. 2002:5). These wave heights are less than the waves simulated by SWAN near the Barrow coastal vicinity. It is possible that during the October 1963 storm, there were 4.6 m waves near the Barrow coast, but far away enough to be out of visual range by observers near the shore. Because of the large-scale computational grid used in these wave simulations, simulated waves in the Barrow coastal vicinity may be up to 5 to 10 km away from the shoreline. This would allow distance for these wave heights to decrease before making contact with the shoreline.

Wave simulations for the rest of the historical storms produced waves where the wave heights and directions were a direct function of the wind speed and direction. Winds from a given direction produced waves of the same direction. The exception was near the coastline where the shallow bathymetry would bend the wave direction into the coastline. This occurred in all the cases where the wind and offshore wave direction were relatively parallel (directions of east, northeast, west, and southwest) to the Alaska North Slope coast. An example is shown in Figure 13.
The wave simulations for the 11 historical storms displayed wave conditions that could be expected under certain wind and sea ice conditions for the study area. The wave simulations for the 29 July 2003 storm showed how wave conditions change with the changing wind conditions that would actually occur during that passage of a storm near Barrow.

One of the most significant changes in the wind conditions during the 29 July 2003 storm occurred between 28 July 7 PM and 29 July 1 AM. For these times the winds were of moderate speeds, 7.8 to 10.3 m/s (17 to 23 mph), and their direction moved from southwest to south. The wave directions changed very little between the two wave simulations, but the maximum offshore wave heights doubled. The location of these maximum wave heights also changed from the northeast quadrant of the SWAN grid to the northwest quadrant (Figures 7 and 8). These two wave simulations had been run a second time to check for errors, and the same results were produced. Large changes in the location of the maximum wave heights were not observed between the other wave simulations for the July 2003 storm. The cause for the change in the location of the maximum wave heights that occurred at the beginning of the storm is unknown at this time.

The maximum wave heights from the July 2003 wave simulations occurred for the 6-hour time period ending 29 July 1 PM. The wave heights were 5.4 m offshore and 4.6 m in the Barrow vicinity. These results are significant to the ability to predict wave heights in the Chukchi/Beaufort Seas and in the Barrow coastal vicinity. Before the storm hit its peak, the marine warning issued by NWS in Barrow predicted waves 5 to 6 m (15 to 20 feet) offshore, which is consistent to the offshore wave heights from the SWAN model (Barrow NWS Office 2003). After the storm past, the observers at the NWS in Barrow estimated wave heights of 4 to 5 m (10 to 15 feet) near the shore (North Slope Borough Emergency Response Team Storm Report 2003). These observed wave

Figure 13. (a) Wind direction (black arrow) and wave direction (blue arrows) contours (degrees x 10^1) for 12 September 1986 wave simulation. (b) Wind direction (black arrow) and wave direction (blue arrows) contours (degrees x 10^1) for 3 October 1963 wave simulation.
heights are also consistent with the wave heights in the Barrow coastal vicinity from SWAN.

CONCLUSION

The SWAN wave simulations have given us more knowledge of the wave heights that can potentially be reached with high wind speeds over the study area of the Barrow coastline and offshore in the Beaufort/Chukchi Sea. With the knowledge of these wave heights the potential wave set-up height may be calculated along the shoreline and incorporated into developing total coastal flood height lines. Further research is needed to study wave heights within 1 km of the Barrow shoreline because of the potential changes in wave heights and directions that can occur as waves approach the shore. These changes could occur from changes in the bathymetry within a few hundred meters of the shoreline redirecting waves or significantly reducing the wave heights before the waves break on the beach.

The knowledge of the potential wave heights and directions is very important to the Beaufort/Chukchi Sea and Point Barrow region because there is a lack of raw data including wave height measurements and accounts of wave directions. With a better understanding of the potential wave heights offshore and in the Barrow coastal vicinity, forecasted wave heights can be incorporated with forecasted storm surges as storms move through the Point Barrow region. This will improve forecasting a total coastal flood height for the Barrow community, which would give community members knowledge of specific sites in Barrow that are at risk to flooding. Steps can then be taken by the community to protect the more vulnerable locations of Barrow.

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