Implications of Ice Cover on Storm Surge Dynamics in the Beaufort Sea

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Introduction

The Beaufort Sea (Figure 1) is located off the northern coasts of Alaska and Canada and is bounded by the Chukchi Sea to the west, the Arctic Ocean to the north, and Banks and Victoria Islands to the east (International Hydrographic Organization, 1953). Ice cover is pervasive throughout most of the year in the Beaufort Sea with open water conditions becoming more prevalent in the late summer months (Rogers, 1978). The formation of the coastal shelf system results in the extensive build up of sea ice (including the presence of fast ice) through much of the coastal areas (Reimnitz et al., 1994). Long-term trends, however, show that the areal extent of the sea ice in the Beaufort Sea has been decreasing due to various factors (Barber and Hanesiak, 2004).

Significant storm surge events have also been recorded in the southern Beaufort Sea. A peak water level of 3.4 meters above mean sea level was surveyed from debris lines along the coast of Alaska following a major storm event in 1970 (Reimnitz and Maurer, 1979). Similarly, a peak water level of 2.4 meters above mean sea level was recorded near Tuktoyaktuk (the main coastal settlement in the region) for the same event in 1970 (Harper et al., 1988). Typically, the greatest surge events occur during open-water season in the late summer. However, surge events have been recorded for heavy ice cover periods during the winter months even with the presence of fast ice.

Recent years have shown a renewed interest in the Canadian Beaufort Sea as part of planned coastal resource development projects. Given the harsh environment that exists throughout the region, field measurements with relatively continuous historical meteorological, wave, or water level data are sparse. As a result, Environment Canada launched the Meteorological Service of Canada Beaufort (MSCB) project to address the lack of *in situ* meteorological and validation data, and to produce high-quality climatology data of the area. These previous efforts resulted in improved hindcast products for both wind field data and wave heights (Swail et al., 2007). The influence of storm surge and astronomic tides were not included in this previous climatology study.

The study reported herein details the development of a storm surge model for the Canadian Beaufort Sea and the associated influence of variable ice cover on surge results. Historical data and hindcast products produced from previous climatology studies of the area are used to drive the development of the storm surge model. The model is validated for several storm events under various sea ice conditions. The result of this project is a finite element mesh that will serve as a component for future climatology and coastal resource development studies within the Beaufort Sea.

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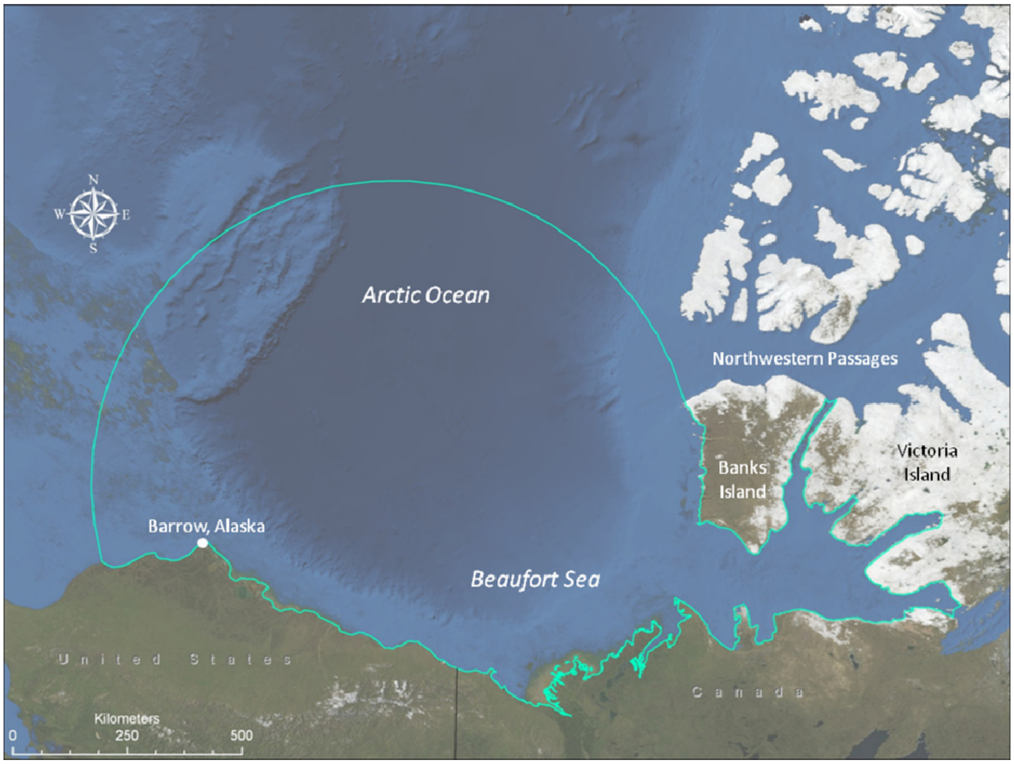

Figure 1. Beaufort Sea and surrounding regions.

Model Description

Hydrodynamic Model

Water surface elevations are computed by the fully nonlinear two-dimensional, depth-integrated option of the Advanced Circulation model (ADCIRC-2DDI) for shelves, coasts, and estuaries (Luettich et al., 1992). The governing equations are discretized in space by linear finite elements and in time by a finite difference scheme. The finite element solution to the shallow water equations gives rise to spurious modes and numerical instabilities. ADCIRC-2DDI employs the Generalized Wave Continuity Equation, together with the momentum conservation equations, to eliminate this problem (Westerink et al., 1994). The result is a noise-free solution that is used to solve for the deviation from the geoid and velocities in the longitudinal and latitudinal directions.

Boundary Conditions

Accuracy of model results near-shore is largely dependent on the specification of accurate harmonic boundary conditions along the open ocean boundary. Therefore, the ocean boundary is placed in relatively deep water, whereby the flow behavior is linear and tidal constituents may be accurately specified. The AODTM5 tidal database (Padman and Erofeeva, 2004) is used to extract eight harmonic boundary conditions ($M_2, K_1, O_1, N_2, K_2, Q_1, P_1$ and S_2) for each model node along the open ocean boundary.

Constituent	Name	Period [hr]	Frequency [rad/s]
M_2	Principal lunar semidiurnal	12.42	0.000140518917083
K_1	Luni-solar diurnal	23.93	0.000072921165921
O_1	Principal lunar diurnal	25.82	0.000067597751162
N_2	Larger lunar elliptic	12.66	0.000137879700000
K_2	Luni-solar semidiurnal	11.97	0.000145842317201
Q_1	Larger lunar elliptic diurnal	26.87	0.000064958541129
P_1	Solar diurnal	24.07	0.000072510563024
S_2	Principal solar semidiurnal	12.00	0.000145444119418

Table 1. Tidal constituents used as boundary conditions in the ADCIRC model.

Wind Field Data

Wind field data is provided by Oceanweather, Inc. (OWI) through their Interactive Objective Kinematic Analysis (IOKA) system (Cox et al., 1995). Due to scarcity of *in situ* marine wind measurements, coastal weather station measurements are transformed into effective over-water wind field data at 10 meters above the water surface. These wind fields are then checked against QuickSCAT data to adjust any systematic errors before being imported into OWI's Wind WorkStation (Swail et al., 2007). The kinematic analysis concentrates on the reanalysis of peak storm events within the continuous period while retaining the QuikSCAT adjusted background fields for day-to-day conditions. The final wind field model produces 30-minute average marine exposure winds at 10 meters above the water surface, reported in hourly increments for the entire model domain.

Bathymetry Data

Two different sources are used to develop the underlying bathymetry dataset for this project: 1) a high resolution bathymetry dataset for the nearshore regions of the Beaufort Sea; and 2) ETOPO1, a global 1-min gridded digital elevation model (DEM) for the ocean regions beyond the Southern Beaufort Sea (Amante and Eakins, 2008). The nearshore dataset was generated through a combination of existing contour maps, field sheets and navigational charts, and SAR data of the ice bottom. No smoothing is required at the interface between these two datasets as both datasets are reasonably consistent for the purposes of this project. A gridded DEM representation of the combined dataset is shown in Figure 2.

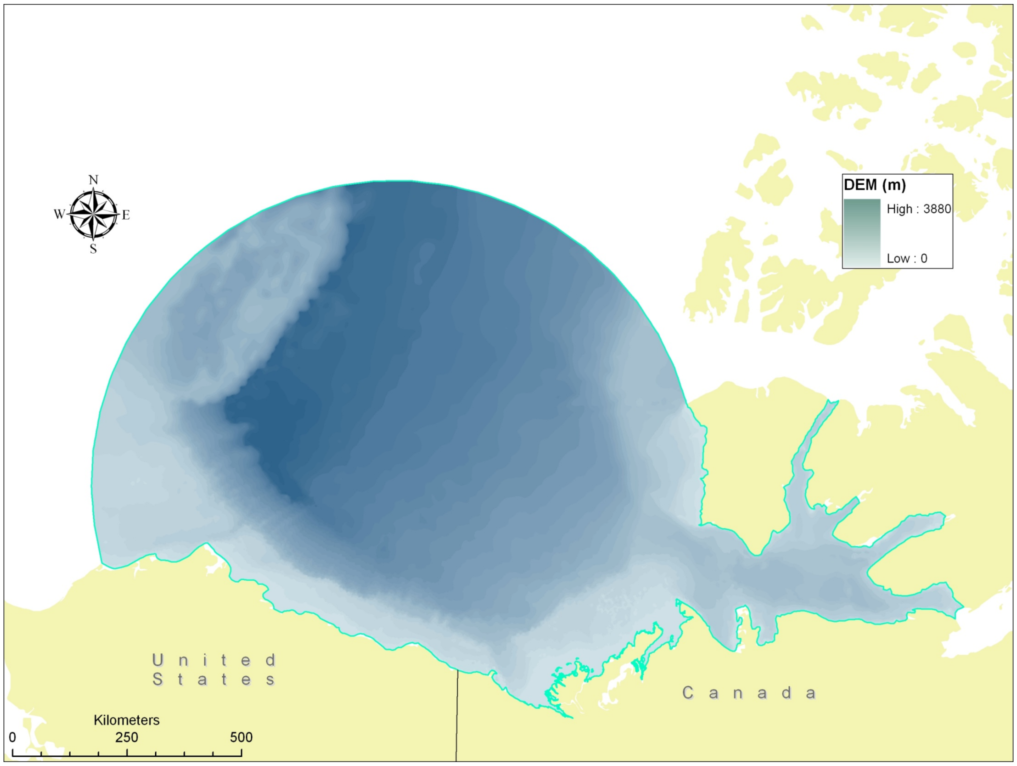

Figure 2. Bathymetry data (depth relative to mean sea level) used to support model development.

<u>Coastline Data</u>
A high resolution coastline shapefile for the Southern Beaufort Sea was provided by the Geological Survey of Canada (GSC) to support mesh development throughout the region. The high resolution coastline file was created through desktop reconnaissance in combination with a georeferenced Landsat image of the region by geologists at the GSC. This coastline shapefile is used to generate the mainland and island boundaries throughout the coastal region, which are treated as no-flow boundaries in the ADCIRC model.

<u>Finite Element Mesh</u>
The high resolution, nearshore bathymetry data had a spatial resolution of approximately 200m-400m between data points. Due to potential nearshore model applications in the coastal zone, mesh resolution is specified such that average node spacing is consistent with the bathymetry dataset. Minimum node spacing goes down to approximately 100m-150m in a few local areas to reasonably describe flow conveyance between some of the smaller islands. Overall, this level of resolution allowed for many of the smaller (and narrower) coastal features to be included in the model domain. Figures 3 and 4, respectively, show the finite element mesh and corresponding node spacing throughout the model domain.

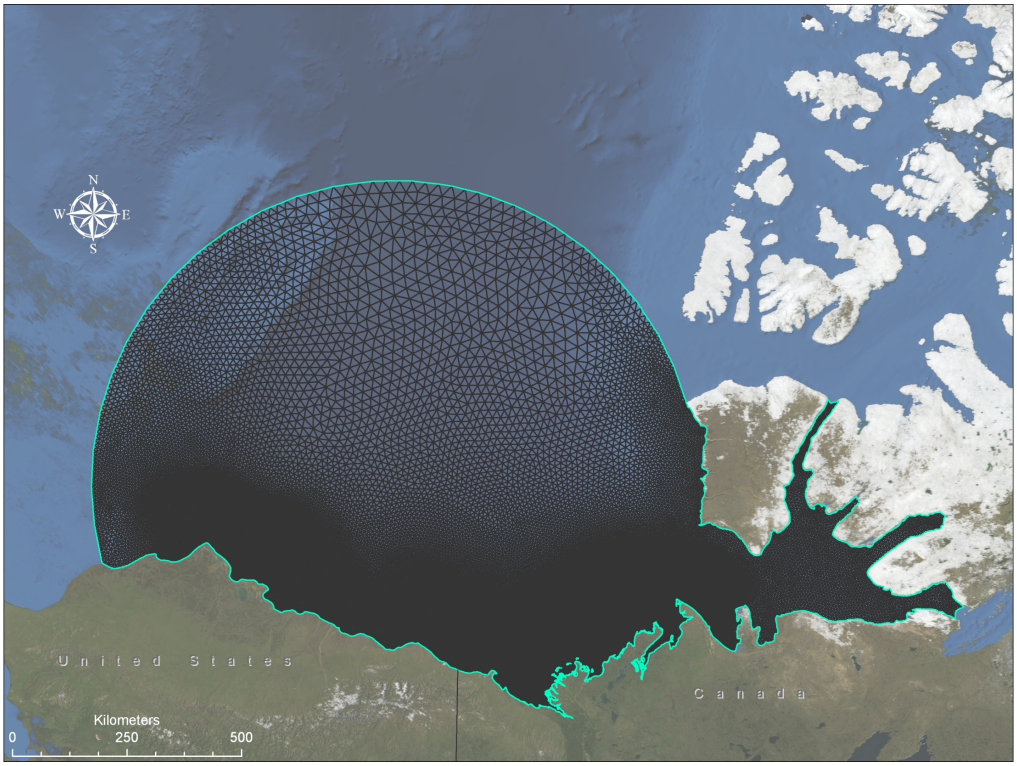

Figure 3. ADCIRC finite element mesh developed for this study.

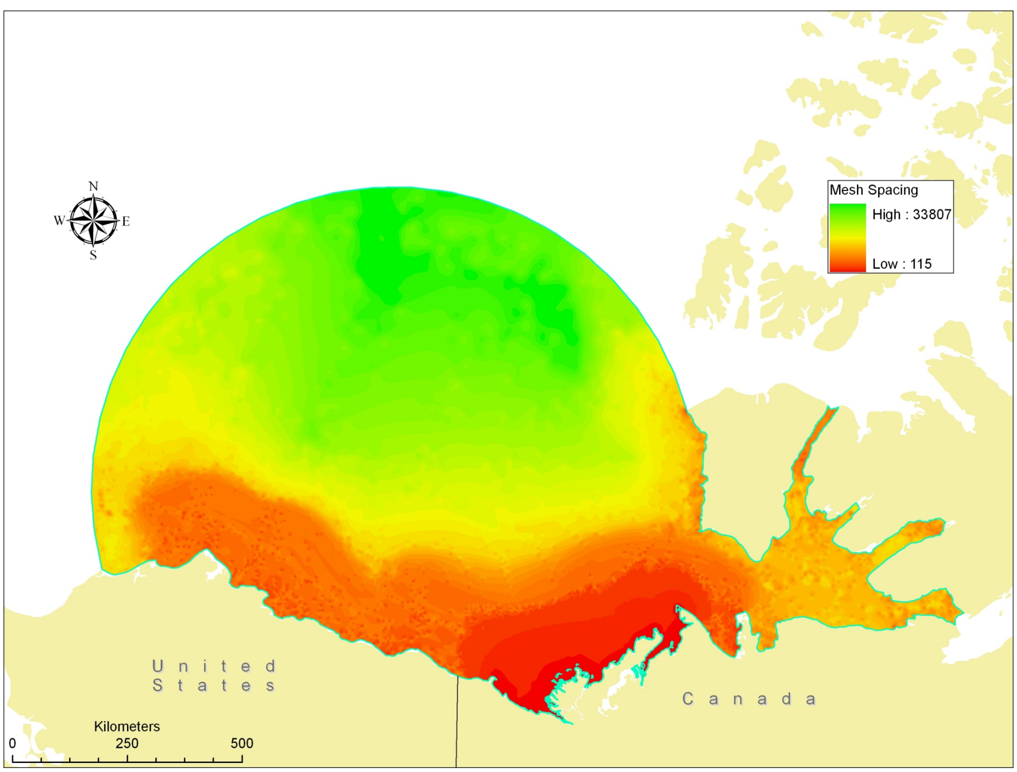

Figure 4. Average node spacing (meters) throughout the ADCIRC model domain.

Open-water Validation

In order to verify that the model is appropriate to simulate storm surge in the Beaufort Sea, a storm event occurring during relatively open water conditions (i.e. minimal ice coverage) is chosen as a test case: August 6, 2004 to August 20, 2004. Wind field data specific to this storm event are used to force the model along with astronomic tide boundary conditions that have been shifted to the beginning of this time period.

Model results are compared at the Tuktoyaktuk water level gauge (DFO Station Number 6485; Figure 5), which is the only DFO station with reliable data during this time period. Figure 6 provides a comparison between the model results and historical data at the Tuktoyaktuk gauge. Overall, model results (blue line) compare very favorably with the historical data (black line). The peak water levels are nearly identical (0.96 meters from model results and 0.94 meters from historical data) and the phasing of the modeled surge event and corresponding tides are nearly identical to the measured data. It is clear from this comparison that the model accurately reproduces the historical surge in the region and is a good tool for open water cases.

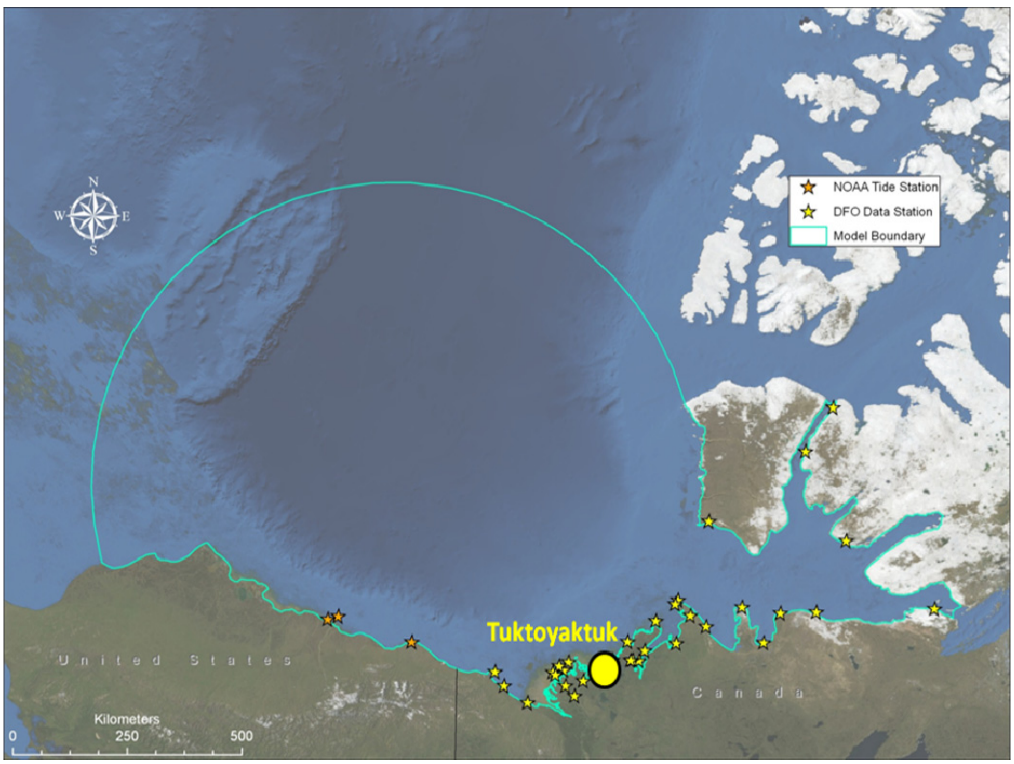

Figure 5. Location of the Tuktoyaktuk water level gauge (DFO Station Number 6485).

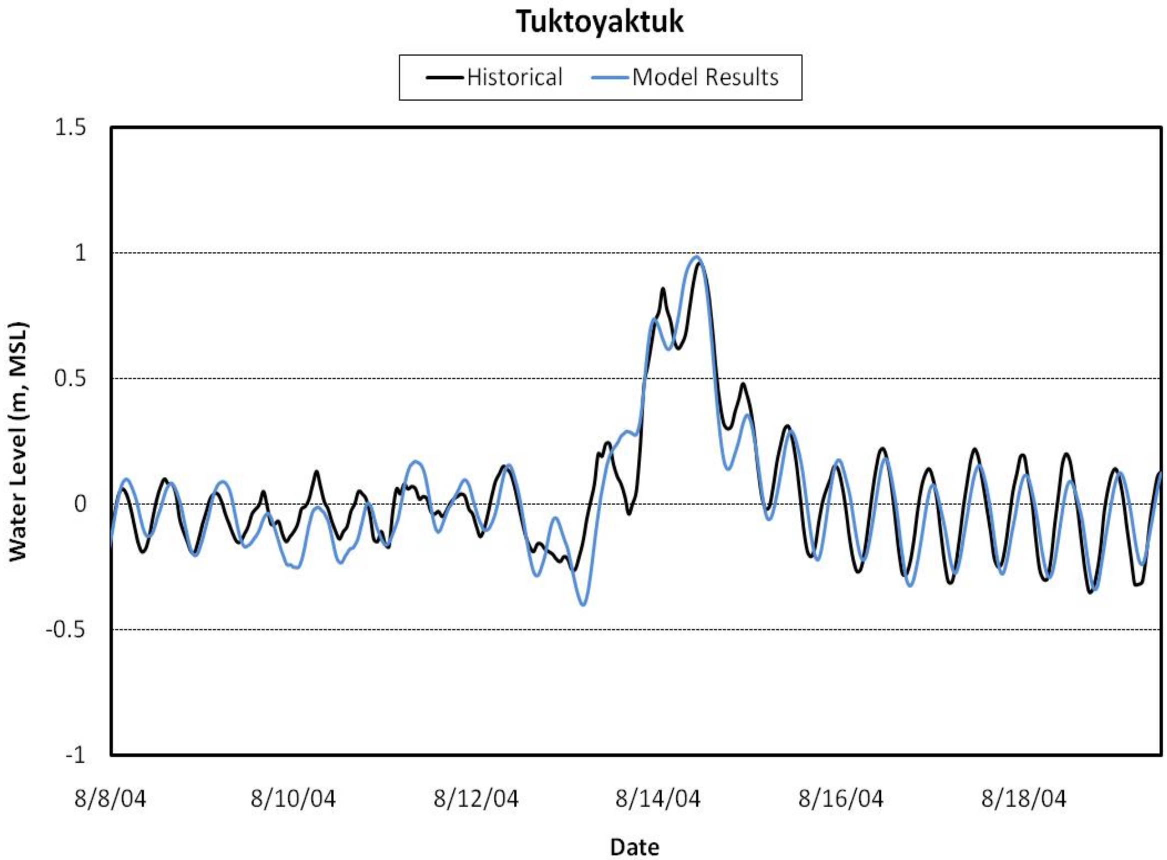

Figure 6. Comparison of model results to historical data for a storm surge event during open water conditions.

Ice Cube Method

Wind Stress Adjustment

Typically, wind stresses are computed in the ADCIRC model using a relationship developed by Garrett (1977) that converts marine wind speeds to wind stress without making any adjustments for ice floe that may be present. Specific to the Beaufort Sea, this formulation is reasonable during the relatively warm summer months when ice coverage is minimal and open water conditions persist throughout much of the region (as evident by the open water validation case previously discussed). However, during other times of the year when ice floe is forming and migrating throughout the region to the point of total ice coverage during winter, the Garrett formulation is not appropriate for simulating storm surge.

In lieu of this problem, the United States Army Corps of Engineers developed an alternate method (Jensen et al., 2012) for computing wind stress by factoring in percent ice concentration (aptly named the “Ice Cube” method). Spatial ice cover data is processed and interpolated onto the ADCIRC mesh throughout the entire simulation time period to determine the percent ice concentration at each computational node. This information is then input to a cubic polynomial to determine the revised surface stress at that particular node based on the percent ice concentration and wind speed. The Ice Cube formulation results in an increased peak drag occurring at 50% ice concentration with calculations reverting back to the Garrett value at 0% and 100% ice cover.

Ice Cover Data

Ice cover data from the Canadian Ice Service are downloaded and processed for each event. This data is provided in weekly snapshots of the spatial ice coverage throughout the study domain, and is interpolated onto the finite element mesh to determine the percent ice concentration surrounding each node. These percent ice concentrations are then factored into the Ice Cube method for determining the wind stress at each node throughout each simulation.

As an example, Figures 7-10 show the evolution of the spatial ice coverage throughout October 1976. The warmer colors indicate a higher degree of ice concentration and the cooler colors indicate lower ice concentration. Note that the Southern Beaufort Sea transforms from relatively open water conditions to pervasive ice cover in a matter of a couple weeks during this period. Similar patterns (i.e. rapid changes in marine ice floe conditions) are noted throughout the ice data for this region, especially during the transition period (typically September and October) from the relatively warmer summer months to the colder winter months.

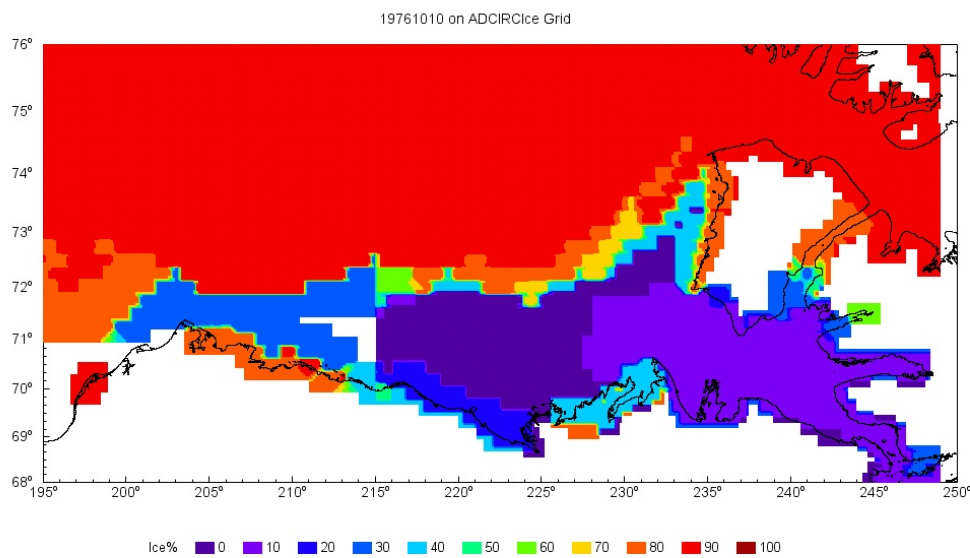

Figure 7. Percent ice concentration throughout the Southern Beaufort Sea on October 10, 1976.

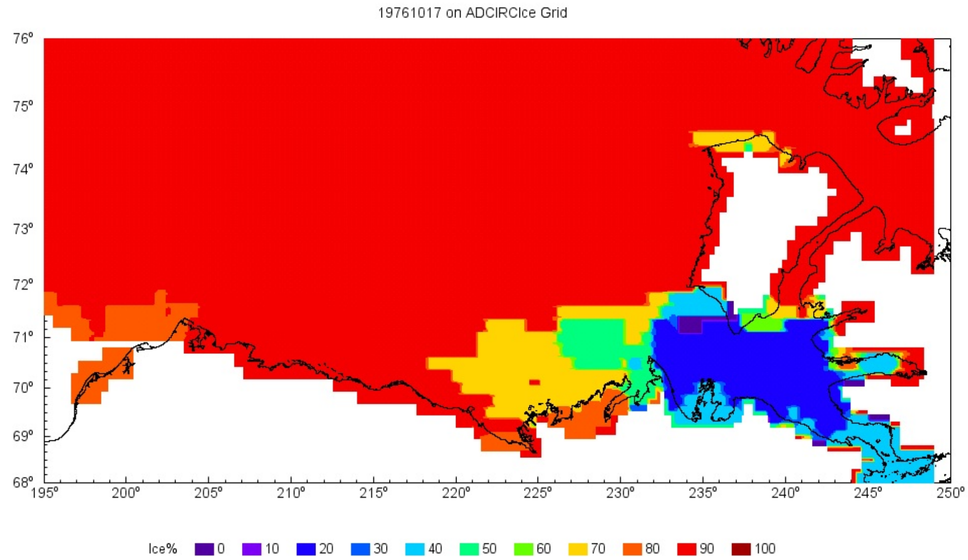

Figure 8. Percent ice concentration throughout the Southern Beaufort Sea on October 17, 1976.

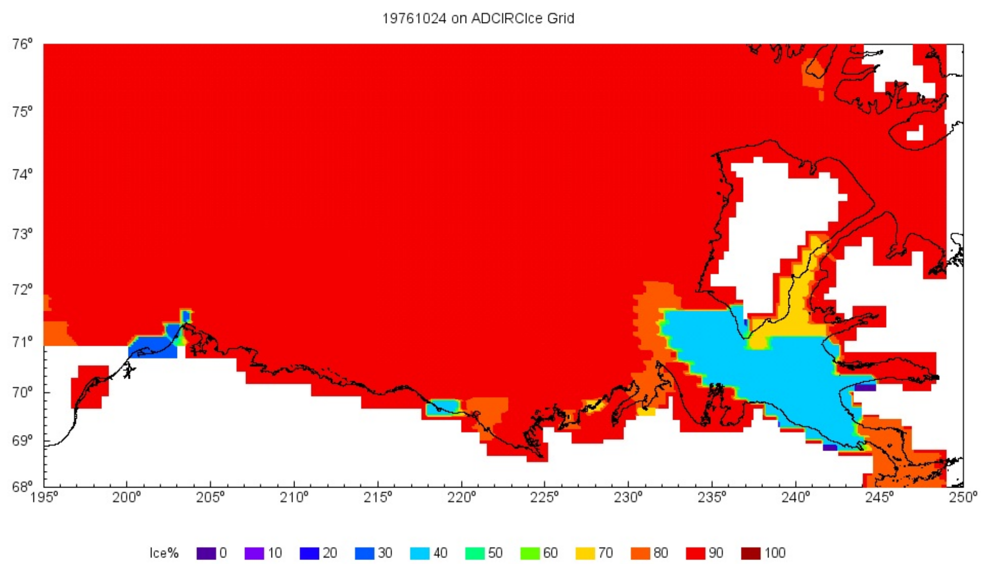

Figure 9. Percent ice concentration throughout the Southern Beaufort Sea on October 24, 1976.

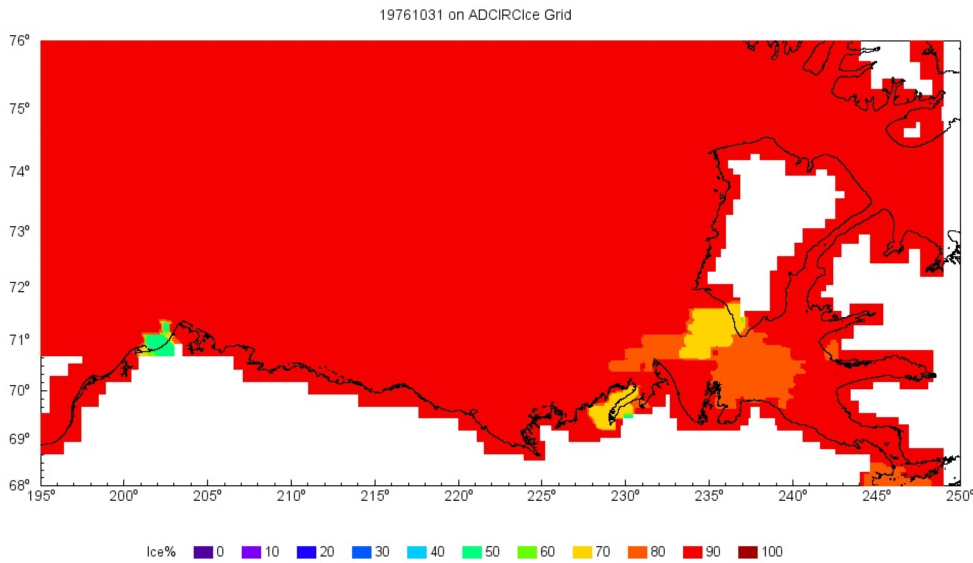

Figure 10. Percent ice concentration throughout the Southern Beaufort Sea on October 31, 1976.

Ice Cover Results

Three scenarios are chosen to test the application of the Ice Cube method for adjusting wind stress in the Beaufort Sea: 1) an open water scenario used to validate the implementation of the Ice Cube method into the modeling system; 2) a transition case with ice floe migrating through the region; and 3) a heavy ice cover event with fast ice pervasive in the coastal zone. For all cases, model results are compared at the Tuktoyaktuk water level gauge (Figure 5) and the appropriateness of the Ice Cube method to that particular event is discussed with an eye toward future long-term continuous hindcast applications.

<u>Open Water Case</u>

The open water conditions scenario (August 6, 2004 - August 20, 2004) is used as a test case to verify the Ice Cube method was properly implemented. Under minimal ice cover, the Ice Cube method should produce similar wind stress as the Garrett formulation. A time series comparison of model results to historical data using both the Ice Cube and Garrett methods is shown in Figure 11. It is apparent from the surge hydrographs that both the Ice Cube and Garrett formulations reproduce the surge response fairly well. Similar to the results presented in Figure 6, there is good agreement in both the amplitude and phase of the modeled surge response when compared to the historical data. Furthermore, peak water levels using the Ice Cube method are similar to those using the Garrett method at the Tuktoyaktuk gauge location with a difference of only 0.011m (the Ice Cube peak is slightly higher). This slight increase in the peak water level is to be expected, even for relatively open water conditions. Ice floe is still present in the northern regions of the study domain and the increase in wind stress is translating itself into slightly higher water levels nearshore.

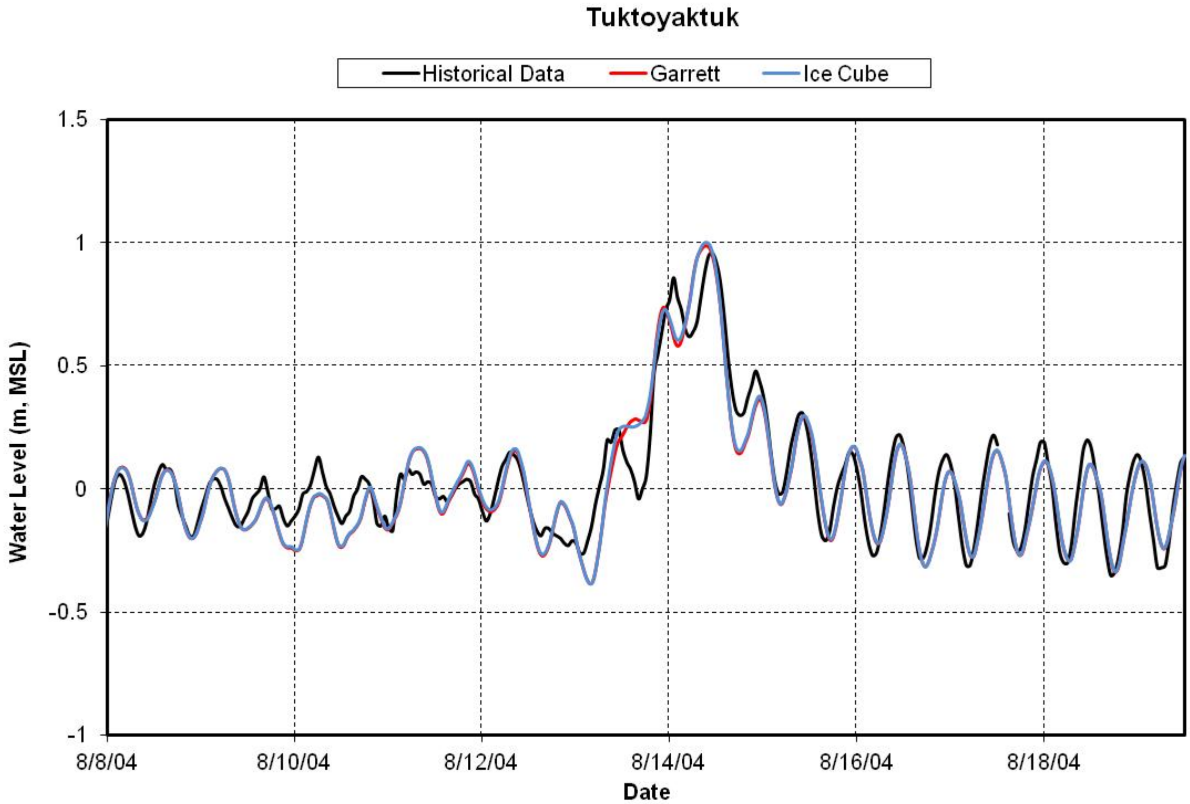

Figure 11. Comparison of model results using the unadjusted Garrett formulation and the Ice Cube method for an open water scenario.

<u>Transition Ice Floe Event</u>

Typically, the months of September and October in the Beaufort Sea represent a time period when ice floe migrates from the northern regions, onto the continental shelf, and builds in the coastal zone. Water level changes can vary considerably during this time period with a sloshing type of behavior to the hydrograph. The Ice Cube method is ideal for these types of applications because it accounts for a range of ice concentrations in the wind stress adjustment, no matter the rate of ice morphology.

September 1980 is chosen as an example ice transition scenario to test the accuracy of the Ice Cube method (Figure 12). Overall, the model results (blue line) are very similar to the historical data (black line) during this time period. In addition to matching the peak water level, the model also captures the sloshing type effect of the historical data (i.e. the constant upward and downward trend of the water level). It is evident from these results that the model system with the Ice Cube method implemented performs well under transition ice floe conditions.

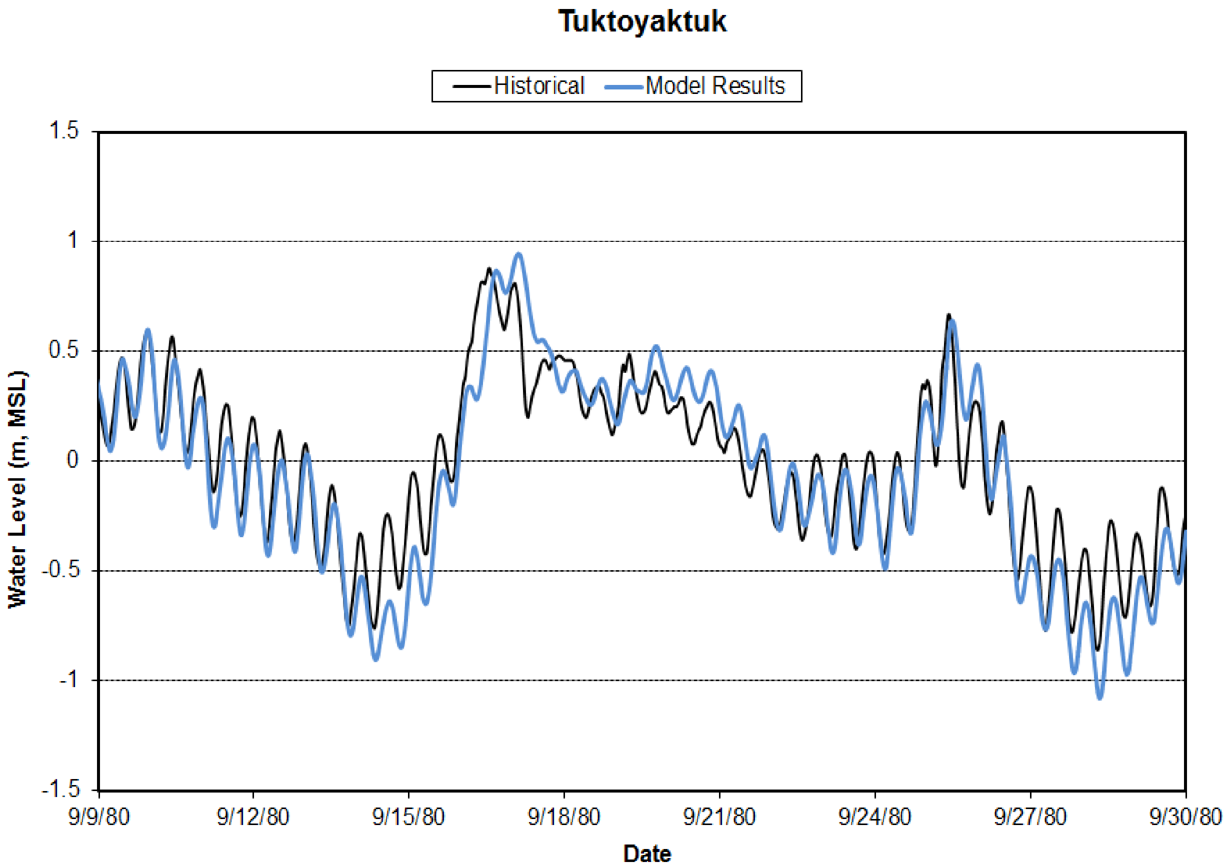

Figure 12. Comparison of model results to historical data for a transition ice floe scenario.

<u>Heavy Ice Cover Scenario</u>

Unlike the warmer summer months and, to a degree, the transition months of early fall, the cold winter months represent a period when the Southern Beaufort Sea is fully covered in sea ice. In some cases, fast ice can develop in the region to the point where the ice sheet is used for transportation purposes. Yet, surge events are still noticeable in the historical data record during these heavy ice cover periods.

December 2008 is chosen as a representative period of heavy ice cover (Figure 13). The same model system with the Ice Cube method implemented is applied for this case as was applied in the open water test case and the transition ice scenario. It is apparent from the results that the Ice Cube method significantly over predicts the surge response compared to the historical data for this time period. The over-prediction in model results during periods of heavy ice cover appears to be a limitation with the Ice Cube method. Based on the equations that are used to derive the Ice Cube method, it is assumed that ice floe moves with the water column and adds to the surface drag. In theory, this approach is valid for application in the marginal sea ice zone or in cases where the ice pack is known to move with the water column. This method does not account for shore-fast ice, which does not move with the water and is prevalent throughout this region (particularly in nearshore regions where the gauge is located).

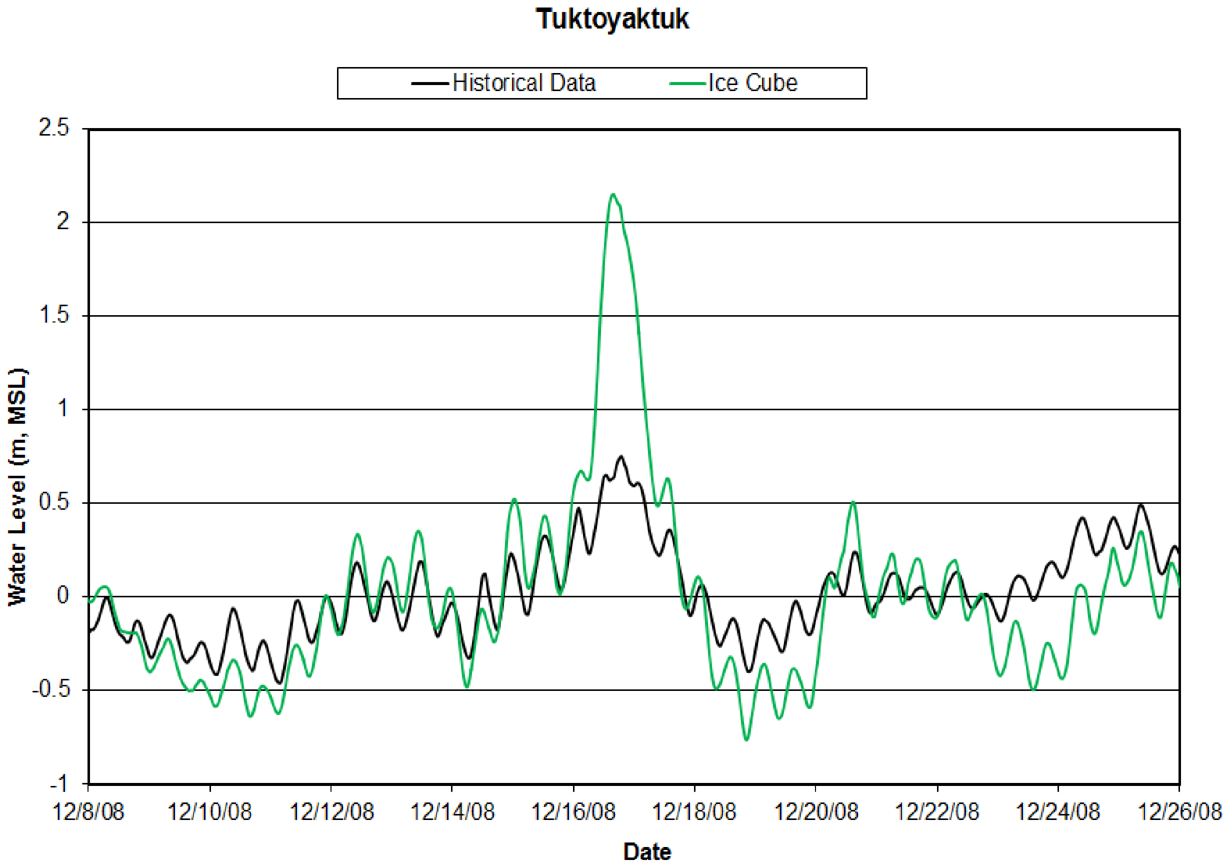

Figure 13. Comparison of model results to historical data for a heavy ice cover scenario.

Adjustments for Shore-Fast Ice

Based on results for the heavy ice cover scenario, it is evident that the model over predicts the surge response when using the Ice Cube method for relatively high percent ice concentrations. Note that the Ice Cube method will either leave the wind stress unadjusted from the Garrett formulation (specifically for 0% and 100% ice cover) or increase the wind stress relative to the Garrett formulation (for any range of percent ice concentration between 0% and 100%). The supporting theory behind this approach suggests that ice floe adds to the momentum transfer between the atmosphere and the water column. However, when factoring in percent ice concentration, the Ice Cube method does not distinguish between ice floe (which moves with the water column) and shore-fast ice (which does not move with the water column). In fact, shore-fast ice is prevalent throughout this region (George et al., 2004) and restricts the transfer of momentum from the atmosphere to the ocean which would significantly diminish the resulting surge response. The spatial extent of shore-fast ice varies constantly and recedes or expands over time depending on a number of factors.

As a first approximation to account for shore-fast ice, the Ice Cube method was modified such that the wind stress was neglected for any computational node that falls within a fast ice region. Weekly ice charts from the Canadian Ice Service (e.g., Figure 14) provide an estimate as to the extents of the types of ice classification throughout the regions. For this case, most of the shoreline in the region corresponds to the "B" ice egg which indicates the presence of fast ice. These regions are translated to polygons in GIS to help identify computational nodes that fall within that particular area. The wind stress value is then neglected for nodes that are selected from this process.

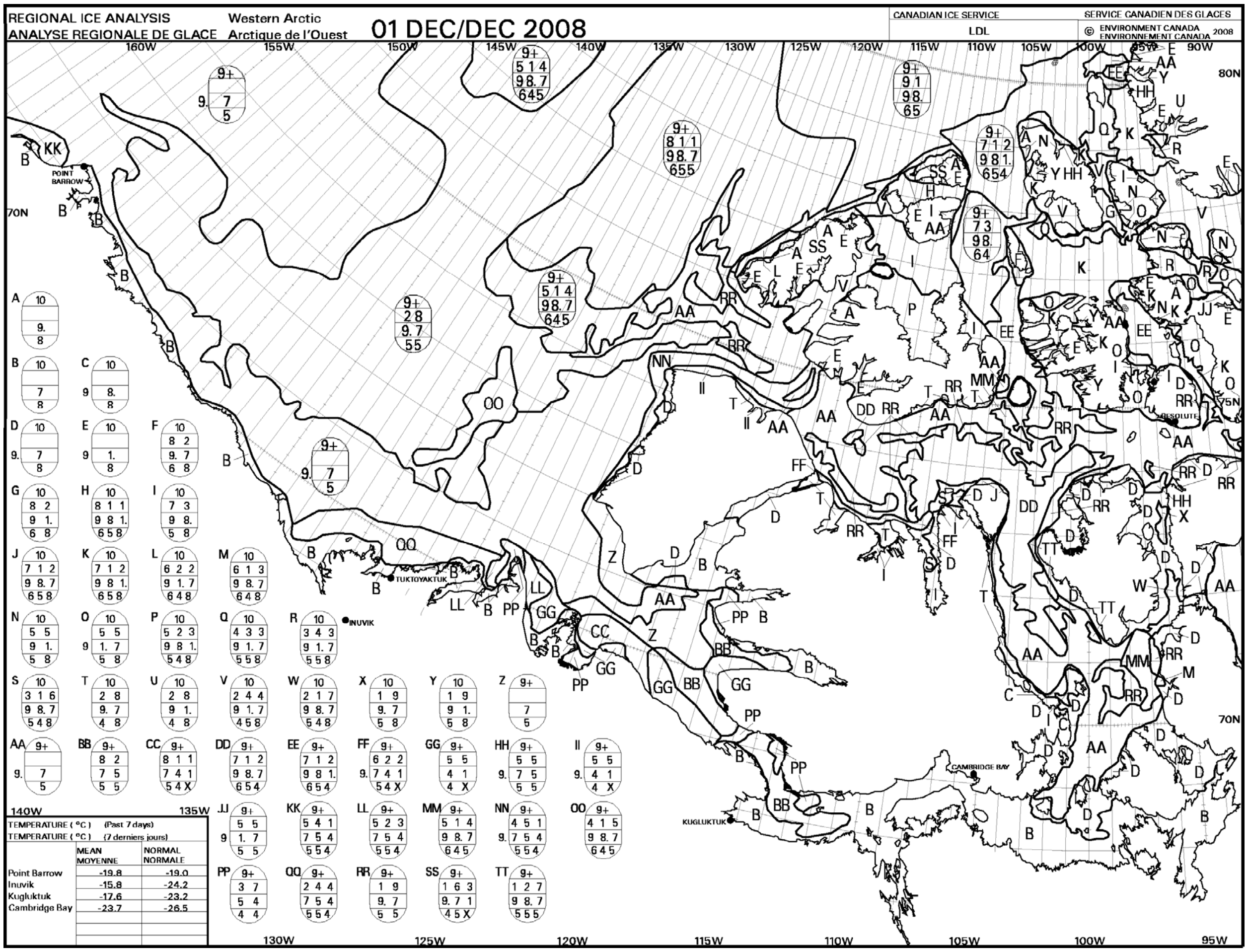

Figure 14. Ice chart for the Beaufort Sea from the Canadian Ice Service for the week of December 1, 2008.

Figure 15 shows the model results using this adjusted method for shore-fast ice at the Tuktoyaktuk gauge. For this case, the model results are significantly improved when implementing the shore-fast ice adjustments. The peak surge, in particular, is much more similar to the historical data than the unadjusted Ice Cube results; however, the model still over predicts the peak water level. Even though the wind stress is neglected for nodes that fall within the fast ice regions, the momentum of the surge entering these shallow areas from deeper waters is enough to carry the surge event to the gauge location, but in a reduced capacity. Also note that the astronomic tide signal is still prevalent in the historical data and the tidal range represented in the model results is consistent with the historical tidal range. While the modeled peak water level is still higher than the measured data, it is apparent that this first approximation to represent fast ice in the model is trending in the right direction. Future work will need to continue developing methods to incorporate fast ice conditions in storm surge models as that is not well understood in the scientific literature at present.

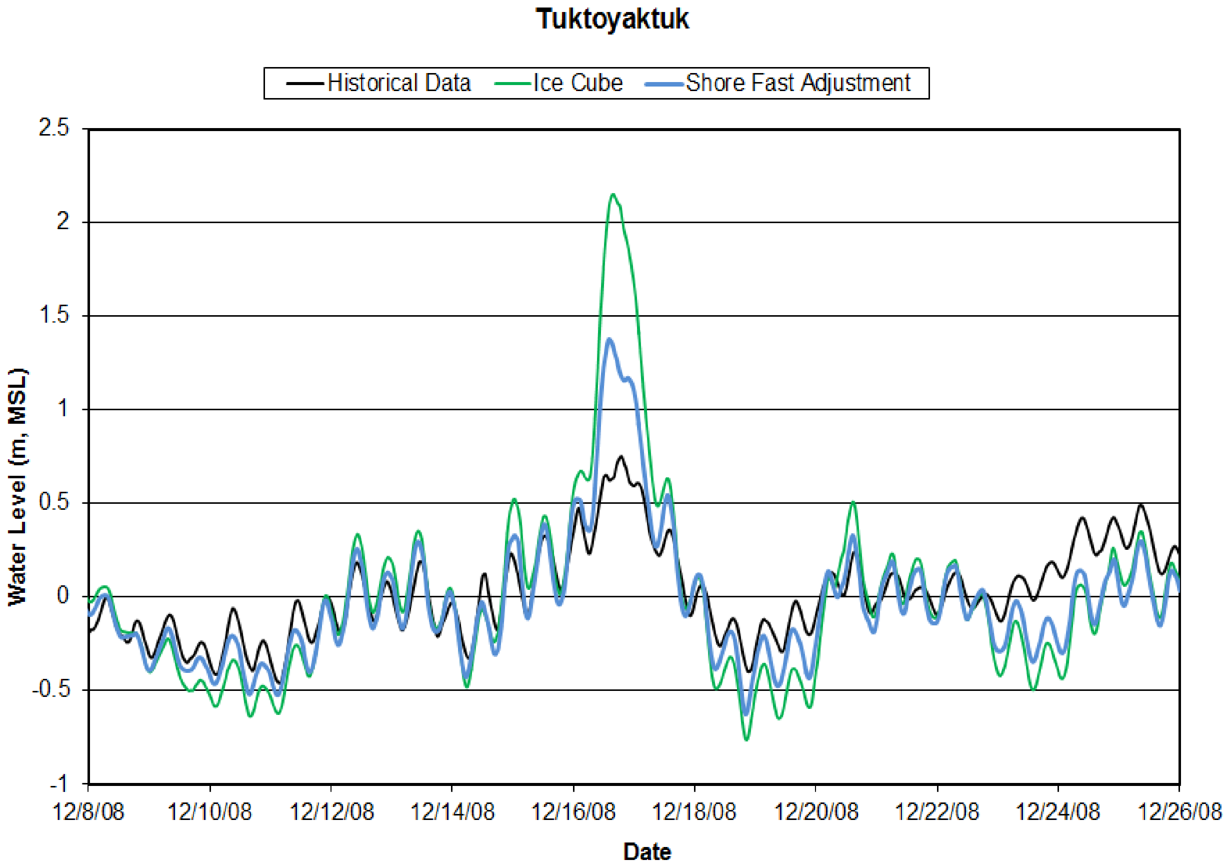

Figure 15. Comparison of Ice Cube results and shore-fast ice adjustment results to historical data for a heavy ice cover scenario.

Conclusions

A storm surge model of the Beaufort Sea is presented for the purposes of simulating surge events for a range of conditions to support long-term climatology studies of the region. Based on model results presented herein, it is evident that the model is ideally suited to simulate storm surge events for open water conditions and transition ice floe conditions.

The Ice Cube method was applied and provided a flexible, yet robust, method for adjusting the wind stress based on wind velocity and percent ice concentration. During periods of migrating ice floe, the Ice Cube method produced results that accurately reflected the historical data. However, periods of heavy ice cover presented complications due to the presence of fast ice in the coastal region. A first approximation to adjusting the wind stress based on the spatial location of the fast ice region was presented that improved the overall model results, but still over predicted the peak surge level.

Future work will need to focus on developing a more robust method for incorporating regions of fast ice into the storm surge model. The approximation method presented herein is reasonable to implement for an event based scenario (i.e. for one or two specific storm events), but is less than ideal for a continuous hindcast application where multiple years of data will need to be simulated.

Acknowledgments

Funding for this study was provided by the Program of Energy Research and Development (PERD) via Environment Canada and the Geological Survey of Canada. The views expressed herein are those of the authors and do not necessarily reflect those of the PERD, Environment Canada, Geological Survey of Canada, or any of their affiliates. The authors also wish to thank Chris Massey of the United States Corps of Engineers Coastal Hydraulics Laboratory for his assistance with the Ice Cube method presented herein, and the late Steve Solomon of Natural Resources Canada for his insight into the coastal dynamics and measurements in the Beaufort Sea.

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