Modeling of Waves and Storm Surge along the Arctic Coast of Alaska

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Abstract

Arctic coasts have been impacted by rapid environmental change over the last 30 years. Warming air and water temperatures and the increased duration of the open water season, correlate with increases of erosion of ice-rich bluffs along the Beaufort Sea coast. Here, we investigate decadal changes in near-shore wave dynamics and storm surge setup as a result of sea-ice retreat.

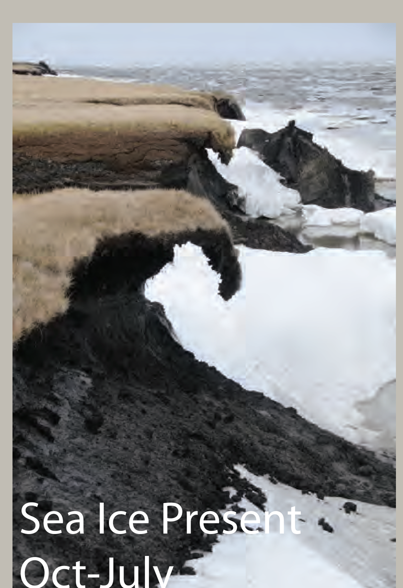
We model wind-driven setup as a function of wind speed and direction, fetch and bathymetry (Dean and Dalrymple, 1991). The wave module calculates the wave field for fetch-limited waves in shallow water based on the Shore Protection Manual (1984). For a given wind speed, dynamic water depth and fetch, we predict the significant wave height and wave period. Both models require fetch as a controlling parameter. Sea-ice influenced coasts are unique in that fetch is temporally variable as the location of the sea ice edge moves through the sea ice free season. We determine the distance this edge using daily Nimbus 7-SMMR/SSM/I and DMSP SSMI Passive Microwave Sea Ice Concentration data.

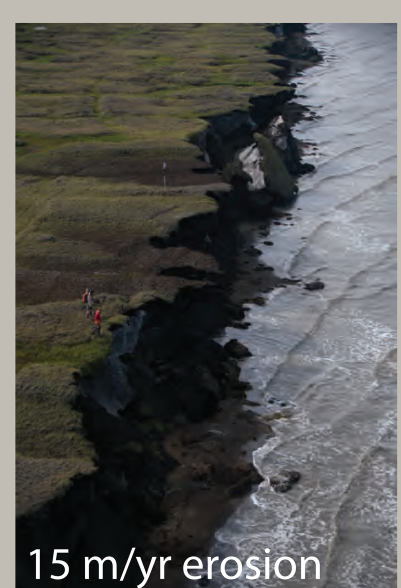
We find a good match between the model predictions and our observed records of meteorological drivers and nearshore water level and waves in the summers of 2009 and 2010.

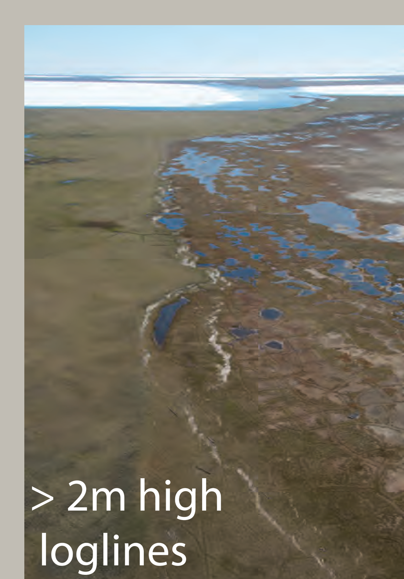
Over the period 1979-2012, fetch has increased significantly. In our study area, the open water season itself lengthened from ~45 days to ~90 days. In the 1980 s and early 1990 s wave dynamics were fetch-limited during a significant period of the open water season. More recently, the distance from the coast to the sea ice edge shifts extremely rapidly (often 100 s of km over 1-2 weeks); fetch therefore only minimally influences wave dynamics as offshore distance exceeds the 140 km threshold over most of the open water season. Waves and wind-driven setup are of importance for flooding of coastal villages.

The Eroding Beaufort Coast

The North Slope of Alaska is a low-gradient tussock and meadow tundra landscape with thousands of thaw lakes. At the Alaskan Beaufort coast ~4 m high ice-rich permafrost bluffs form the abrupt transition of tundra into ocean. These permafrost bluffs have a high ice content, upto ~65% locally. Sea-ice abuts the bluffs for most of the year; the sea ice free season begins roughly in the middle of July and lasts until October. These bluffs are eroding at alarming rate (15 m/yr in 2010 and 2011) (Wobus et al., 2010).

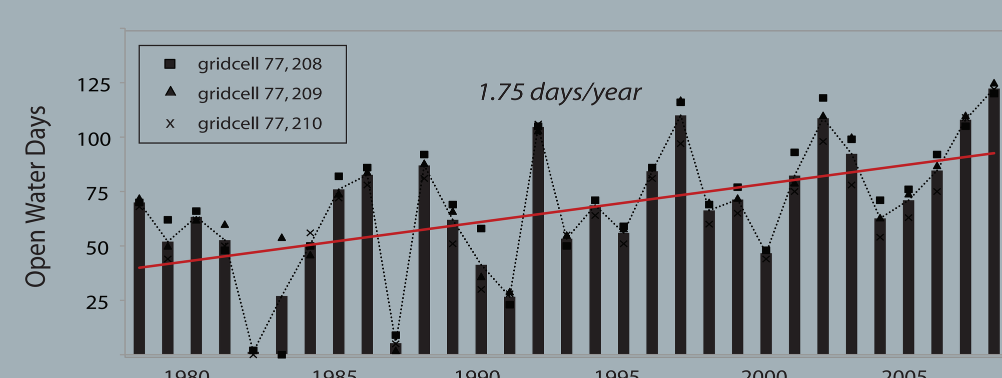




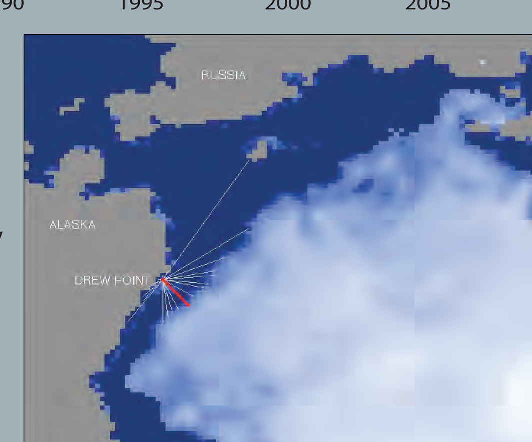


Decreasing Sea-Ice Extent

With rapid Arctic warming the sea-ice free season has expanded. Along a 75km stretch of coast nearby our study site near Drew Point specifically, the nearshore open water season has lengthened from ~45 days in 1979 to ~95 days in 2009 (Overeem et al., 2010).



Open water conditions affect the fetch- the length over which wind set up occurs and waves are generated. Fetch is always variable due to the changing wind field, and coastline geometry but in addition In our Arctic Ocean case the temporally variable location of the sea-ice edge needs to be accounted for



Fetch for Drew Point, July 24, 2007

Overarching Research Question:

What is the anticipated effect of sea ice edge location changes on the wave field and wind-driven set-up at the coast?

Wind-driven Set-up Model

Wind characteristics, fetch and bathymetry are used to drive a bathystrophic surge model (Dean and Dalrymple, 1991). The model predicts wind set up or set down, eta by starting at a distance F away from the coast where the water level is unaffected by the wind-driven shear. Then we calculate the spatial derivative term and move stepwise to solve for the setup at the coast.

For our study area, winds from the West typically set up the local water level, whereas the more common Easterly winds associated with the persistent Beaufort High, set down the nearshore water level.

set-up

$$(h+\eta)\left[\frac{\partial(h+\eta)}{\partial x}-\frac{dh}{dx}-\frac{f_c V}{g}\right]=\frac{n\tau_{wx}}{\rho_w g}$$

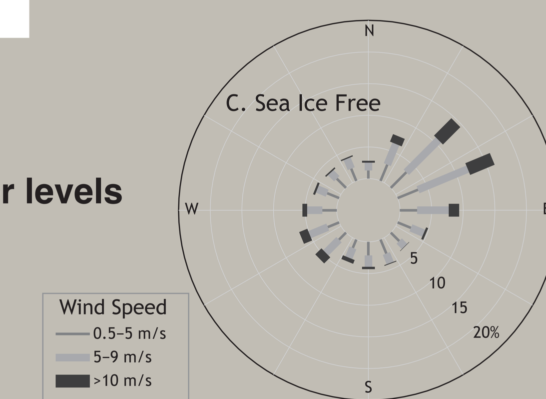
$$\tau_{wx}=\rho_w g k U^2$$

wind shear stress [M/Lt[2]]

$$V=\sqrt{\frac{8k\sin(\theta)}{f}}U$$

depth-averaged alongshore water velocity [L/t]

Westerly Winds yield highest water levels



Wave Model

The bathymetry of the shelf and nearshore is extremely shallow at our study site: the average shelf slope is 0.001 m/m. Buoys deployed at 10 km offshore were in ~ 8 m water depth. At the shoreface the gradient is slightly steeper, we measured a bathymetric slope of 0.0035 m/m in the first 10 m s offshore.

We use the Shore Protection Manual formulation for shallow water, fetch-limited wave generation.

Winds are from the observed long-term record at Barrow, which has been adjusted to match local wind climate with ~ 5 years of observations at Drew Point.

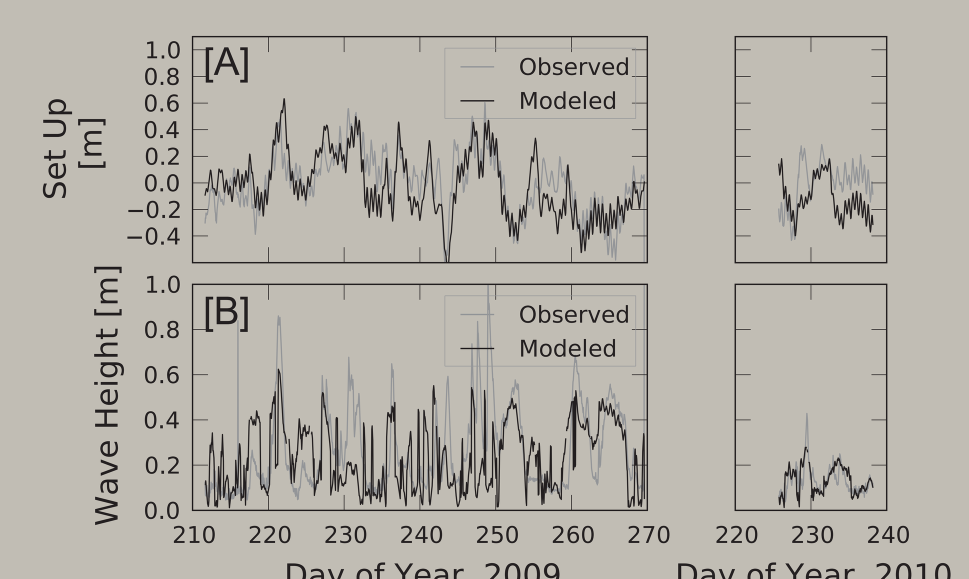
non-dimensional wave height

$$\frac{gH}{U_a^2}=0.283\tanh\left[0.53\left(\frac{gh}{U_a^2}\right)^{\frac{3}{4}}\right]\tanh\left[\frac{0.00565\left(\frac{gF}{U_a^2}\right)^{\frac{1}{2}}}{\tanh\left[0.53\left(\frac{gh}{U_a^2}\right)^{\frac{3}{4}}\right]}\right]$$

$$U_a=0.71\times U_{10}^{1.23}$$

Ua= adjusted wind speed [L/T]

Model comparison to 2009 and 2010 observations



Wave and SST Sensors being deployed in 2009

We collected bathymetric data, wave data, water level data, and sea water temperature data in two separate field campaigns over July-late Sept 2009 and August-Sept 2010.

The setup and wave height data of the most nearshore station (launched in >2m water depth in 2009 and >1m water depth in 2010) have been used to compare to the model predictions.

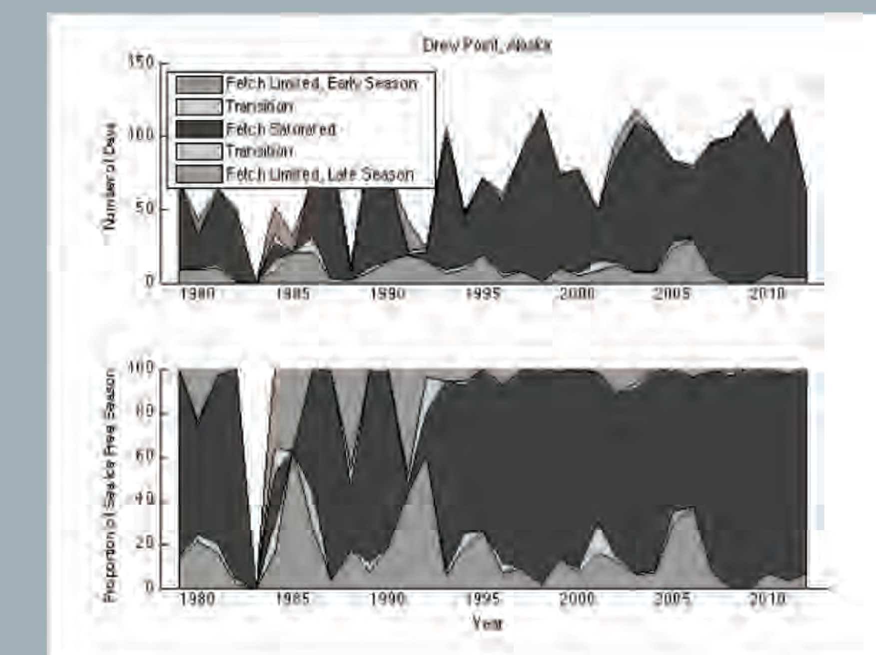
There is a good match between model predictions and observations. Occasional wave height peaks are missed.

Results

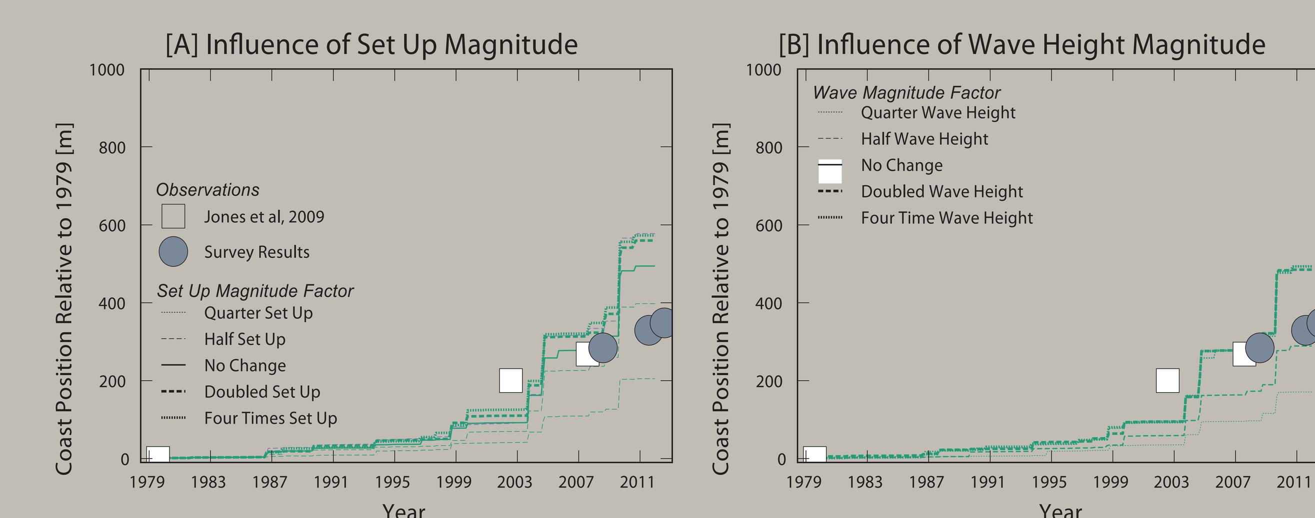
Analysis of the thirty year wind records did not reveal any apparent trends in storm magnitudes or frequencies. However, the lengthening of the open-water season itself results in an increased number of events

Over the period 1979-2012, fetch has increased significantly. At Drew Point, the open water season duration more than doubled. This means that in the 1980 s and early 1990 s wave dynamics were fetch-limited during a significant period of the open water season. More recently, the distance from the coast to the sea ice edge shifts extremely rapidly (often 100 s of km over 1-2 weeks); fetch therefore only minimally influences wave dynamics as offshore distance exceeds the 140 km threshold over most of the open water season.

The dominant winds along this stretch of the Beaufort Coast causes a set-down of the nearshore water. This set-down dampens the potential erosion rates due to thermal notching of the sea water.



Sensitivity of Erosion Model to Wave and Setup



Here we show some key results of the effects of setup and wave climate variation on the 30 year modeled erosion rates.The fully-coupled coastal bluff evolution model of Barnhart et al., (in prep.) shows that thermal notching is more sensitive to sea water temperature and mean water level changes.

Theoretical sensitivity tests have been run to explore the effect of a 4 times increase or 4 times reduction of the magnitudes of setup and waves. The effects on the coastal erosion evolution over 30 years are noticable but less dramatic than expected from the dramatic range in the experiments.

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