Coastal landfast sea ice decay and breakup in northern Alaska: Key processes and seasonal prediction

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Seasonal breakup of landfast sea ice consists of movement and irreversible ice detachment in response to winds or oceanic forces in the late stages of ice decay. The breakup process of landfast sea ice in the Chukchi Sea at Barrow, Alaska, was analyzed for the years 2000 through 2010 on the basis of local observations of snow and ice conditions, weather records, image sequences obtained from cameras, coastal X band marine radar, and satellite imagery. We investigated the relation of breakup to winds, tides, and nearshore current measurements from a moored acoustic Doppler current profiler. Two breakup modes are distinguished at Barrow on the basis of the degree of ice decay. Mechanical breakup due to wind and oceanic forces follows ablation and weakening of the ice. Thermal breakup is the result of ice disintegration under melt ponds, requiring little force to induce dispersion. Grounded pressure ridges are pivotal in determining the breakup mode. The timing of thermal breakup of the nearshore ice cover was found to correlate with the measured downwelling solar radiation in June and July. This linkage allows for the development of an operational forecast of landfast ice breakup. Results from forecasts during 2 years demonstrate that thermal breakup can be predicted to within a couple of days 2 weeks in advance. The cumulative shortwave energy absorbed by the ice cover provides for a measure of the state of ice decay and potential for disintegration. Discriminating between the two modes of breakup bears the potential to greatly increase forecasting skill.


1. Introduction

Much of the Arctic Ocean is ringed by a belt of landfast sea ice, typically a few kilometers to more than 100 km in width. Landfast or shorefast ice protects the coast from the erosive impacts of storms and drifting pack ice [Reimnitz et al., 1994]. It is an important habitat for organisms ranging from ice algae to seals and polar bears, providing a platform for feeding, breeding and resting [Bluhm and Gradinger, 2008]. Landfast ice also plays an important role in the life of Arctic communities, both for travel and hunting, as well as in the context of resource development as an operations platform [Gearheard et al., 2006; Aporta, 2009; Eicken et al., 2009]. At the same time, the presence of landfast ice in late spring limits access to the coastal ocean for hunters and boat travel. Thus, spring landfast ice breakup, either through dispersal or in situ melt, is one of the most important events in the seasonal cycle of coastal environments. It greatly increases access to the coast and adjacent open waters, forces marine mammals with a preference for sea ice platforms offshore and increases the vulnerability of the shoreline to erosive action.

Tracking the timing of breakup on time scales of decades is hence crucial to assess the impacts of climate variability and change on ecosystems and human activities. Moreover, forecasting of breakup, even on time scales of days to a few weeks can be of potential value in preparing for the transition between ice- or land-based winter activities and ocean-based summer activities, whether from the perspective of a coastal village or an industrial operator. Finally, such forecasts may also be useful in the context of management of marine resources, in particular threatened or endangered species such as walrus or polar bears.

Breakup of landfast sea ice in the North American Arctic has been studied mostly in the context of ice trafficability and offshore oil and gas development [e.g., Sackinger and Rogers, 1974; Spedding, 1983; Barry et al., 1979] or coastal dynamics [Short and Wiseman, 1975; Shapiro and

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keeping with common practice we express MDD in °C days.

For the Alaskan Beaufort Sea coast, studies [e.g., Spichkin, 1961; Gudkovich, 1995] as summarized by Gudkovich [1995], warming and ablation (decay) precondition the landfast ice for breakup under the influence of dynamic forces of winds and ocean. In the Siberian Arctic, semiempirical approaches have been employed that rely on one or several factors, such as air temperature, wind speed and ice thickness to predict breakup on time scales of days to a week. While we were not able to find comparisons between model forecasts and observations, Gudkovich specifies predictive success relative to climatology at 20 to 35%. For the Alaskan Beaufort Sea coast, Barry et al. [1979] state that 55 to 140 and 140 to 220 melting degree days (MDD) are required to observe opening and movements of nearshore landfast ice and complete clearance of landfast ice off coast, respectively. Melting degree days are defined as

\[
MDD(t) = \int_0^t \left\{ \begin{array}{ll} 
T_a(\tau) - 0 \, ^\circ \text{C} & \text{for } T_a \geq 0 \, ^\circ \text{C} \\
0 \, ^\circ \text{C} & \text{for } T_a < 0 \, ^\circ \text{C} \end{array} \right\} \, d\tau
\]

where \(T_a\) is the air temperature at time \(\tau\), and \(t\) is the time passed since the beginning of the melt season at \(t = 0\). In keeping with common practice we express MDD in °C days (i.e., \(8.64 \times 10^4 \text{Ks}\)) [Petrich and Eicken, 2010]. However, no models describing summertime breakup have been suggested for the Chukchi Sea coast applicable to Barrow [George et al., 2004].

[5] Other studies have aimed to determine ablation of coastal sea ice and relate ice thickness to summertime breakup. This approach has been motivated by the assumption that thin ice is sufficiently weak to allow dynamic forces of atmosphere and ocean to break up and clear landfast ice off the coast. The role of air temperature as a proxy for the progression of ice decay during spring melt has been investigated by Bilello [1980] for various stations mostly in the Canadian Arctic. He found that 120 to 190 melting degree days were required to remove the ice in 8 out of 10 years investigated at Resolute (initial ice thickness 1.9 ± 0.2 m). Bilello [1980] also investigated the utility of integrated downwelling shortwave radiation as a proxy for decay. Starting integration on the first day air temperatures exceeded 0°C, the cumulative shortwave flux ranged between 730 and 1050 MJ/m² for the same 8 years at Resolute. However, Bilello [1980] did not describe the breakup process at Resolute, leaving it unclear whether ice actually melted in place or drifted out at some point. In recent years, studies of the response of Arctic (coastal) sea ice to climate variability and change included numerical modeling of the seasonal cycle of landfast ice from freezeup to breakup. While these ice models include the combined effect of snow cover, air temperature and radiative balance, they typically rely on the assumption that dynamic breakup takes place at a date at which the simulated ice thickness decreased to a threshold level, ranging between 0.5 m [Dumas et al., 2006] and 0 m [Shirasawa et al., 2005]. All modeling studies acknowledged the contribution of dynamic processes to breakup of weakened ice. However, none of the studies focused on the process or definition of breakup itself. Also, the role of disintegrating ice under melt ponds as opposed to ablation of unponded level ice has not been considered explicitly.

[7] We analyzed an 11 year record of breakup observations at Barrow in a location representative of conditions along the Chukchi Sea coast (Figure 1). For the purpose of this study, breakup is defined as the detectable movement of nearshore landfast ice associated with irreversible deterioration and decay of coastal ice in spring (see section 4). In line with past studies [e.g., Reimnitz et al., 1994; George et al., 2004] we consider landfast ice as an aggregate of grounded pressure ridges and attached shoreward level and rubble ice (“nearshore ice”; see Figure 2). Ice attached seaward of grounded pressure ridges and associated breakout events were considered elsewhere [Druckenmiller et al., 2009] (“attached ice”; see Figure 2). In years without grounded pressure ridges, that typically help define nearshore ice, breakup corresponds to the final removal of that stretch of ice that remains longest attached to shore at a particular location. The present study aims to characterize the breakup process and investigate its predictability in the context of forecasts on time scales of several weeks.

[8] We derive a data set of breakup times and modes by analyzing ground-based observations recorded by a web camera, a coastal radar and ice observers as well as satellite–remote sensing data to arrive at a better understanding of the landfast ice breakup process at Barrow and examine its variability on the time scale of a decade. While the date of

Figure 1. Bathymetric map of Barrow, Alaska. The locations of the 2010 oceanographic mooring B1 and NOAA tide gauge 9494935 are indicated. Bathymetry contours are in meters [Lestak et al., 2003].
breakup is determined by the coastal topography as well as a range of other factors discussed below [Mahoney et al., 2007a], the landfast ice at Barrow is representative of ice conditions and processes along a wider stretch of coastline in the Alaskan and East Siberian Arctic [Barry et al., 1979; Druckenmiller et al., 2009]. The breakup process will be discussed in the light of available wind, current and tidal data, and thermal decay. Building on the analysis of ice breakup and its interannual variability we then present a simple empirical model to forecast decay and breakup of landfast ice on time scales of days to 2 weeks. The breakup model is forced by a near-real-time long-range Alaska weather forecast system (http://knik.iarc.uaf.edu/AtmGroup/ForecastGraphics.htm), which is using the Weather Research and Forecasting (WRF) model [Skamarock et al., 2005] configured for the regional conditions of Arctic Alaska.

2. Ice and Ocean at Barrow

[a] We describe a general, simplified picture of ice conditions in the Chukchi Sea with a focus on Barrow, Alaska (Figure 1). The Chukchi Sea coast runs SW to NE from Point Hope to Point Barrow with the Alaska Coastal Current generally moving to the northeast, with occasional 2 to 10 day periods of current reversal [Aagaard and Roach, 1990; Weingartner et al., 1998]. The Barrow Canyon approximately parallels the Chukchi coast about 30 km offshore at Barrow, resulting in a steep bathymetric gradient with the 20 m water depth contour as little as 1 km offshore. The landfast ice edge typically extends out to the 20 to 25 m isobath once a stable landfast ice cover has formed [Mahoney et al., 2007a]. At Barrow and elsewhere along the Chukchi and Beaufort Sea coast, grounded pressure ridges are found at this water depth, helping stabilize the shorefast ice [Rex, 1955; Barry et al., 1979]. In the Beaufort Sea east of Point Barrow, the 20 m isobath follows the coast in excess of 10 km offshore. Point Barrow presents a small protrusion to the northwest into the Chukchi Sea. While the semidiurnal tidal sea level variability is less than 0.3 m, the range of sea level variations due to surges can exceed 1 m [Hume and Schalk, 1967; Lynch et al., 2008]. In spring and summer, warm waters entering the Chukchi Sea through Bering Strait are steered by bathymetry to follow systematic flow paths [Weingartner et al., 2005; Woodgate et al., 2005]. Most of the variance in currents is explained by local winds [Johnson, 1989; Weingartner et al., 2005; Woodgate et al., 2005]. Warm waters were observed to contribute most directly to ice melt where they flow perpendicular to the edge of the marginal ice zone and where ice is advected into warm currents [Paquette and Bourke, 1981; Ahlnäs and Garrison, 1984]. At Barrow, those waters flow approximately parallel to the shore and landfast ice edge in the Alaska Coastal Current [Weingartner et al., 2005].

[10] With the Chukchi Sea generally ice free during summer in recent years, the ice extent increases from late October to cover the entire Chukchi Sea by late December. While historically landfast ice at Barrow typically started to form during the first week of October [U.S. Navy Hydrographic Office, 1958], observations during the recent decade showed landfast ice to form in Barrow no earlier than November [Gearheard et al., 2006]. However, newly formed landfast ice is prone to breaking out during storms, resulting in years of landfast ice formation as late as mid-December (e.g., 2006 and 2007, and presumably some years between the 1930s and 1950s [U.S. Navy Hydrographic Office, 1958]). Landfast ice present in late December will remain in place until breakup in summer.

[11] Usually ice conditions in winter are conducive to the formation of grounded pressure ridges between 500 m and 2 km off the Barrow coast with sail heights in excess of 3 m. The sheltered nearshore zone between grounded pressure ridges and shore is filled with pack ice, formerly landfast sea ice that drifted in from elsewhere, and ice that grew in place [cf. Shapiro and Barnes, 1991]. This conglomerate of nearshore ice can be divided into 100 m to kilometer-size patches of either deformed, rubble ice (surface ice profile variation in excess of 0.2 m) or level ice (i.e., surface profile variations are not apparent without dedicated measurements).

[12] Our measurements at Barrow [Druckenmiller et al., 2009] show that ice thickness of level nearshore ice increases from 0.6 to 0.8 m in January to reach its maximum of 1.4 to 1.6 m in mid-May. The mean snow depth on nearshore ice can be less than 0.1 m in early January. Snow dune depth may exceed 0.3 m in early May. Snowmelt begins in May and patches of bare ice and melt ponds appear in early June. Melt pond formation is generally first observed offshore of downtown Barrow in May where snow is often visually dust covered, and progresses northward over the following days or weeks until it reaches UIC-NARL and Point Barrow in the first half of June. Owing to their low albedo compared to bare

Figure 2. Schematic cross section of landfast ice along the Chukchi Sea coast at Barrow, Alaska, during the melt season (see section 1 for details). Thick arrows indicate pathways of direct and indirect ice melt from solar radiation. Photo insert illustrates preferential melt under melt ponds on 15 June 2009.
or snow covered sea ice [Grenfell and Perovich, 2004], melt ponds greatly enhance surface ablation and internal melt of sea ice. The typical length scale of snow dunes and melt ponds is 5 to 15 m (cf. insert in Figure 3). Barrow experiences perpetual daylight from 11 May until 1 August. In addition to surface ablation, decreased sea ice surface albedo and a reduction of ice concentration in the Chukchi Sea allow increased solar heating of the ocean, contributing to ice decay by increasing the porosity of sea ice and promoting bottom melt of level ice and pressure ridges (Figure 2).

3. Methods

3.1. Ice

[13] The sea ice melt season has been recorded by a webcam positioned at various locations between downtown Barrow and the research support center at the Ukpeagvik Iñupiat Corporation Naval Arctic Research Lab (UIC-NARL) since 2000. The Webcam overlooked shore, ice and sky at UIC-NARL during the summers 2000 to 2005 (2000–2003: 71.33°N 156.68°W, 10 m above ground; 2004–2005: 71.33°N, 156.67°W, 8 m above ground, facing WNW) and at downtown Barrow since the melt season 2006 (71.29°N, 156.79°W, 23 m above ground, facing NNW). Images were recorded every 5 min. Ridged and rubble ice features and summer melt ponds can be discerned, allowing detection of ice motion. Image contrast is too low to discern features on days of low visibility; that is, on a few days in June and July. The best overview of ice conditions off UIC-NARL was obtained 2000–2003.

[14] Scattering of radar signals off sea ice surface features provides distinct return signals that are used to track sea ice motion. A Raymarine X band 10 kW radar (10 GHz, 3 cm), recording one image every 5 min was placed at UIC-NARL in the summers of 2004 and 2005; that is, within the footprint of earlier radar observations [Sackinger and Rogers, 1974; Shapiro and Barnes, 1991]. In 2006, a Furuno 12 kW X band radar was permanently installed next to the webcam in downtown Barrow. At a range of 10 km data from the radar downtown extend past UIC-NARL and provide spatial continuity for breakup observations. Webcam, radar, and routine ice observations are part of the Barrow coastal observatory and accessible online (http://seaice.alaska.edu/gi/) [Druckenmiller et al., 2009].

[15] To supplement the coastal observations in spring and summer we used satellite images, primarily from the optical systems Moderate Resolution Imaging Spectrometer (MODIS, onboard satellites Aqua and Terra) and Landsat. Reprojected Landsat images were obtained through the USGS Global Visualization Viewer, while reprojected MODIS images since 2004 were provided by the NASA MODIS Rapid Response System. In addition, we reprojected Level 1B MODIS images from 2000 to 2003 with the USGS MODIS Reprojection Tool–Swath. Although visible satellite images are subject to clouds, we obtained valuable information to supplement the radar and webcam observations owing to generally light cloud coverage in Barrow in June and July.
and a comparatively high rate of overpasses of Aqua and Terra satellites, providing a combined 8 to 12 potentially usable overpasses daily. RADARSAT and European Remote Sensing Satellite (ERS-2) Synthetic Aperture Radar (SAR) images to complement the analysis were provided by the Barrow Area Information Database (BAID) project.

3.2. Ocean

[16] Nearshore oceanographic measurements are available at Barrow during 2 years of the investigated period. From August 2008 until August 2010, the National Oceanic and Atmospheric Administration (NOAA) operated moorings 3.5 km northwest of UIC-NARL (station 9494935, 71.36°N, 156.73°W), recording sea level data with pressure transducers every 6 min (Figure 1). In addition, we deployed a nearshore oceanographic mooring with Teledyne Sentinel WH-300 acoustic Doppler current profiler (ADCP) ~36 m beneath the sea surface, and Sea Bird Electronics SBE 37 and 39 instruments as part of the coastal observatory from August 2009 until August 2010. Velocity data were recorded in 2 m vertical intervals every 15 min. The mooring, referred to as B1, was located 7 km west of UIC-NARL at a water depth of 42 m (71.325°N, 156.884°W; see Figure 1). Data are available through the Cooperative Arctic Data and Information Service of the Arctic Observing Network (http://aoncadis.org).

3.3. Atmosphere

3.3.1. Observed Irradiance

[17] Downwelling broadband irradiation measurements are available through the Department of Energy Atmospheric Radiation Measurement (ARM) program starting in 2000. Automated measurements performed northeast of UIC-NARL on tundra are generally available with 3 to 5 day delay. ARM data are the reference irradiance in this study, and the latest data available are used during the breakup forecast.

3.3.2. Weather Station Data

[18] We use hourly aviation routine weather reports (METAR) of the Barrow airport (PABR) to obtain a historical record of air temperature, wind speed and direction, and historical and up-to-date information on both cloud cover, respective ceiling height and runway visibility to estimate downwelling shortwave flux. The airport is located near downtown (71.29°N, 156.76°W). For breakup forecasts, we bridge the temporal gap between ARM data and forecasts with irradiance estimates on the basis of the METAR record. The method of estimating downwelling shortwave radiation on the basis of cloud, visibility and day of year is described in Appendix B.

3.3.3. Weather Forecast

[19] The atmospheric forcing for the breakup forecast is the hourly output at Barrow from the 16 day long-range Alaska weather forecasts. The forecasts are produced by the Weather Research and Forecasting (WRF) model in which the initial and boundary conditions are driven by the 16 day extended forecasts of the Global Forecast System (GFS) operated by the National Centers for Environmental Prediction (NCEP). The WRF forecast domain is centered over the Seward Peninsula, Alaska on the polar stereographic projection and is bounded by latitudes 50°N and 80°N, by the New Siberian Islands and by Banks Island. The horizontal resolution of the forecast domain is 20 km. [20] The Alaska WRF forecast system is configured with model physics of the Goddard shortwave [Chou and Suarez, 1994] and the Rapid Radiative Transfer Model (RRTM) longwave [Mlawer et al., 1997] for the radiation transfer calculations, and the land surface model NOAH [Chen and Dudhia, 2001] for surface physical processes, in which the surface albedo of 0.65 is used for a grid cell covered by sea ice. Ice coverage (either 0% or 100%) and sea surface temperature are prescribed by the GFS forecasts.

[21] Our investigations with ARM irradiance measurements show that the WRF forecasted downwelling shortwave irradiance is biased. In order to improve the irradiance forecast we apply an empirical correction, which is outlined in Appendix B.

4. Results

4.1. Breakup Process

[22] A description of the breakup process of landfast ice at Barrow from summer 2000 to summer 2010 is provided in Appendix A. Here, we summarize these observations through specific examples. Observations show that two fundamental modes can be discerned. In years with grounded pressure ridges the nearshore ice decays in place (surface water visible between pieces of white ice in Figure 4a) until winds and currents are able to move it along the coast while pressure ridges remain in place (as seen in Figure 4b showing a different configuration of nearshore ice while pressure ridges are still in place). Over the course of days or weeks after the initial dislocation and movement of nearshore ice (Figure 4c), pressure ridges break out or melt in place (Figure 4d). On the basis of interpretation of webcam images, no evidence of fracturing of islands of unpended level ice at breakup could be observed, suggesting that ice beneath melt ponds had either melted completely or weakened to fail and allow for drift under moderate forces. Since the controlling factor in the breakup process is the melt of ice under melt ponds we refer to this mode of breakup as thermal breakup. The other fundamental mode appears in years of few or absent grounded pressure ridges that allow weaker dynamic forces to trigger breakup. In this case ice has weakened and the nearshore ice and pressure ridges fracture under the influence of mechanical forces, breaking out simultaneously during weather events and clearing the shore within hours. Hence, we refer to this breakup mode as mechanical breakup.

[23] For consistency we define breakup as the first day on which movement of ice nearshore is detected at UIC-NARL. Breakup happens generally earlier in years of mechanical breakup than in years of thermal breakup (cf. Table 1 and Appendix A). While breakup is defined on the basis of point observations, the process can be placed into broader context with the help of satellite images. As an example of thermal breakup, consider the sequence of events illustrated in Figure 5 showing MODIS imagery for 2006. The defining feature is the persistence of pressure ridges offshore extending tens of kilometers south of Barrow (not shown) while nearshore ice melts and moves alongshore, and the presence of an ice plug north of Point Barrow preventing flushing of nearshore ice to the north. First signs of complete melt offshore of downtown Barrow appear on 3 July. Nearshore ice moved south at UIC-NARL on 6 July as recorded by the coastal radar. Disintegration continued north of UIC-NARL,
Figure 4. Sequence of webcam images of breakup at UIC-NARL in the summer of 2000. (a) Ice is decaying in place. (b) Nearshore ice is moving to the southwest (i.e., to the left). (c) Nearshore ice cleared with only grounded ice still in place (1 km offshore). (d) Ice floating at the coast and almost all grounded ice broken out.

Table 1. Breakup Mode and Timing, Melting Degree Days at Breakup, and Cumulative Irradiance at Breakup, Starting With the Integration on 5 June

<table>
<thead>
<tr>
<th>Year</th>
<th>Nearshore Ice</th>
<th>Mode</th>
<th>Starting</th>
<th>Pressure Ridges Period</th>
<th>Melting Degree Days (°C days)</th>
<th>Cumulative Irradiance (MJ/m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2000</td>
<td>thermal</td>
<td>10 Jul</td>
<td>29–31 Jul</td>
<td>113</td>
<td>700</td>
<td></td>
</tr>
<tr>
<td>2001</td>
<td>thermal</td>
<td>5 Jul</td>
<td>7 Jul</td>
<td>80</td>
<td>710</td>
<td></td>
</tr>
<tr>
<td>2002</td>
<td>- a</td>
<td>30 Jun</td>
<td>1–15 Jul</td>
<td>51</td>
<td>499</td>
<td></td>
</tr>
<tr>
<td>2003</td>
<td>mechanical</td>
<td>25 Jun</td>
<td>24 Jun</td>
<td>33</td>
<td>498</td>
<td></td>
</tr>
<tr>
<td>2004</td>
<td>mechanical</td>
<td>18 Jun</td>
<td>18 Jun</td>
<td>50</td>
<td>356</td>
<td></td>
</tr>
<tr>
<td>2005</td>
<td>thermal</td>
<td>8 Jul</td>
<td>13–16 Jul</td>
<td>62</td>
<td>762</td>
<td></td>
</tr>
<tr>
<td>2006</td>
<td>thermal</td>
<td>6 Jul</td>
<td>4–9 Aug</td>
<td>115</td>
<td>701</td>
<td></td>
</tr>
<tr>
<td>2007</td>
<td>mechanical</td>
<td>27 Jun</td>
<td>27 Jun</td>
<td>66</td>
<td>584</td>
<td></td>
</tr>
<tr>
<td>2008</td>
<td>thermal</td>
<td>8 Jul</td>
<td>17–19 Jul</td>
<td>121</td>
<td>723</td>
<td></td>
</tr>
<tr>
<td>2009</td>
<td>thermal</td>
<td>11 Jul</td>
<td>15–18 Jul</td>
<td>119</td>
<td>711</td>
<td></td>
</tr>
<tr>
<td>2010</td>
<td>mechanical</td>
<td>4 Jul</td>
<td>4 Jul</td>
<td>50</td>
<td>697</td>
<td></td>
</tr>
</tbody>
</table>

*aSee section 4 for 2002 data.
with drift past Point Barrow possible after 11 July. A clear passage past Point Barrow was open on 22 July, while grounded pressure ridges were still in place offshore 2 weeks later on 4 August. The coast was ice free on 9 August. The stability and the protecting effect of grounded pressure ridges can be observed between 11 and 22 July when pack ice moves in and closes the coastal lead while the region shoreward of the pressure ridges remains ice free.

[24] A case of thermal breakup in an ice year more typical for the last 11 years is illustrated in Figure 6 for the year 2008. That year, the defining feature was the development of an open passage for ice drift to the north at about the same time as nearshore ice became mobile. Once the ice had been weakened in place, it was flushed out of the coastal zone to the north. Landfast ice north of Point Barrow was dislodged between 30 June and 5 July. First signs of open water were present at the shore on 7 July with signs of nearshore ice redistribution by 8 July. A clear passage for nearshore ice to drift north past Point Barrow existed from 9 July onward. The flaw lead lining the outer landfast ice edge opened and pack ice retreated 13 July, leaving grounded pressure ridges behind. Remaining ice drifted off on 23 and 24 July. The complexity of ice drift patterns at the time of breakup is not apparent from MODIS imagery. For example, while the coastal radar recorded motion to the northeast in the coastal lead from 3 to 17 July, nearshore ice south of UIC-NARL moved along the shore to the southwest to enter the lead between Barrow and Browerville (Figure 1) on 7 June and on several occasions thereafter.

[25] Figure 7 illustrates mechanical breakup in 2007. The defining features are ice breaking out successively along the coast south to north without preceding nearshore ice movement. The lead was open with landfast ice in place on 20 June. Some ice was lost south of Barrow and along the lead edge by 25 June (see also Figure 3). All landfast ice was broken out by 28 June, with only one ice island still grounded offshore of Barrow. Not shown is a RADARSAT image of 26 June revealing that landfast ice was still in place that day. Mechanical breakup in the form of ice breaking out at UIC-NARL occurred on 27 June, documented by coastal radar.

[26] Breakup dates and the period of disappearance of pressure ridges at UIC-NARL are summarized in Table 1 and shown in Figure 8 (Appendix A). We classify breakup in 2003, 2004, 2007, and 2010 as mechanical, and all other years, except 2002, as thermal. 2002 remains unclassified because both ice formation and breakup processes were unusual. In 2002, grounded pressure ridges did not form until March, with the water between the coastal shorefast ice and pressure ridges freezing afterward. In this case we consider breakup as the movement of the original shorefast ice rather than the earlier (7 June) movement of the thinner ice that formed since March. In addition to differences in landfast ice formation, surface melt may have progressed differently in 2002 compared to other years investigated. Using ARM data of tundra albedo as a proxy, in 2002 snowmelt and melt pond formation proceeded in a two stage evolution, first significantly advancing around 25 May, but then being temporarily stalled by a cold spell and overcast conditions until early June.

4.2. Dynamic Forcing

[27] Throughout the year, winds at Barrow come predominantly from easterly directions between 5 and 10 m/s (10 to
20 knots) (Figure 9a). Wind speeds on days of breakup were typically around 5 to 7 m/s (Figure 10); that is, within the range of commonly observed wind speeds at Barrow, with the strongest winds of ~10 m/s observed in 2003, 2005, and 2007. Winds were observed to come from any direction during breakup, except from south and southeast (Figure 10). In 6 out of 11 years, winds came from westerly directions (2001, 2002, 2004, 2005, 2009, 2010), while winds blow from westerly directions less than 25% of the time in June and July (Figure 9b). This difference is statistically significant at the \( p = 0.05 \) level. The direction of ice drift during thermal breakup was recorded by webcam and coastal radar. Nearshore ice drifted to the southwest in years with winds from either easterly (2000, 2006) or westerly directions (2001, 2002, 2009). Drift to the northeast was only observed in 2 years. In 2005, winds blew from westerly directions, while in 2008 the wind direction changed from east to northwest at the time of breakup. While ice motion during the general breakup period in 2008 was complicated (see above), in all years for which we have radar observations of drift in the coastal lead during thermal breakup, ice in the coastal lead and nearshore ice at UIC-NARL drifted predominantly in the same direction (2006, 2008, 2009).

In 2010, data are available on currents and sea level near UIC-NARL. Measurements during the breakup period are shown in Figure 11 with breakup and notable

Figure 6. MODIS visible-range composite images for the Barrow region during thermal breakup of 2008. Images show an area \( \sim 30 \text{ km} \times 40 \text{ km} \) in size; pixel resolution is 250 m. Arrows indicate regions of change; see section 4.1 for details.

Figure 7. MODIS visible-range composites near Barrow during mechanical breakup of 2007. Images show an area \( \sim 30 \text{ km} \times 40 \text{ km} \) in size; pixel resolution is 250 m. Arrows indicate regions of change; see section 4.1 for details.
breakout events before and after breakup highlighted (cf. Appendix A). Ocean temperatures during breakup period ranged between $-2$ and $6^\circ$C at 36 m depth, and currents more that 2 m below the sea surface were moving to the northeast with the exception of the 2 days preceding a breakout event at downtown Barrow on 25 June (cf. Figure 12). Notably, the brief period with currents to the southwest was associated with water temperatures decreasing to the freezing point, while currents to the northeast were associated with temperatures rising. A notable change in wind direction from southwest to north occurred during breakup on 4 July. Sea surface level variation was small with the highest sea level recorded following 8 July and lasting during the breakout event dislodging grounded ridges on 9 July. Also, both sustained wind speeds and near-surface currents peaked at 10 m/s and 1.1 m/s (cell 15 in Figure 11), respectively, at the end of 8 July.

4.3. Ice Decay

[29] Figure 13 shows the accumulation of melting degree days until breakup with the final values listed in Table 1. By the date of thermal breakup, ~110 to 120 melting degree days have accumulated, with the exception of 2001 and 2005, where thermal breakup occurred at between 60 and 80 melting degree days. Years of mechanical breakup experienced the complete removal of all ice at UIC-NARL after 30 to 70 melting degree days.

[30] Figure 14 shows the cumulative irradiance at the time of breakup for different start dates of integration. While the cumulative irradiance decreases as the start of integration approaches the date of breakup, it is noticeable that the years of thermal breakup and 2010 are closely clustered compared to the remaining years. For years of thermal breakup the range of cumulative irradiance is lowest for start days around day 158. As an example, we consider a start date of 5 June; that is, the date used for the breakup forecast. On the basis of a start date of 5 June, years of thermal breakup accumulated between 700 and 760 MJ/m$^2$, while years of mechanical breakup and 2002 experienced breakup after 560 to 590 MJ/m$^2$, with the exception of 2010 in which 700 MJ/m$^2$ were accumulated (Table 1). The irradiance trajectories are shown as a diagram of cumulative irradiance versus average irradiance in Figure 15. Comparing average irradiance early in the melt season with average irradiance at breakup we notice that some years show little correspondence (2000, 2005, 2006) while other years are consistently low (2009) or high (2004, 2007). At the time of breakup, the average irradiance was highest in the 4 years of mechanical breakup (2003, 2004, 2007, 2010).

4.4. Forecast

[31] Using the cumulative irradiance as an indicator for thermal breakup, we operated a breakup forecast during the
melt seasons 2009 and 2010 (presented in the Study of Environmental Arctic Change (SEARCH) Regional Sea Ice Outlook; www.arcus.org/search/seaiceoutlook). Breakup was forecast to take place as soon as a threshold cumulative irradiance was reached. Figure 16 shows the range of error in the breakup prediction for different start dates of integration. The calculations are performed in hindsight; that is, on the basis of actual ARM irradiance measurements rather than irradiance forecasts. For each start day in Figure 16, the cumulative irradiance threshold for breakup was chosen to be the lowest cumulative irradiance observed at breakup. The best performance would have been obtained for a starting day of year 158; that is, 7 June (cumulative irradiance threshold 655 MJ m$^{-2}$). However, we performed the operational breakup forecast on the basis of a start date of 5 June for consistency with past predictions. Operating the breakup forecast with both measurements and irradiance predictions, Figure 17 illustrates the history of predicted breakup dates for the 2009 season, a year of thermal breakup. Until 26 June, the breakup forecast was indicating that breakup was expected outside the range of the weather forecast. From 26 June on, the breakup forecast was consistent to within 1 day and eventually fell on the exact date of observed breakup.

Breakup in 2010 was classified as mechanical breakup and is thus outside of the range of applicability of the forecast. However, the 2010 breakup forecast was consistent to within 2 days since 20 June (not shown), and the predicted date was off by 1 day.

5. Discussion

5.1. Breakup Process

Our observations show that landfast ice breakup at Barrow is a two stage process where thermal decay of near-shore ice is followed by dynamic forces that cause the near-shore ice to dislodge, defining breakup. In years without grounded ice offshore (mechanical breakup), the landfast ice weakens from heat supplied by ocean and atmosphere. In response to dynamic forces, large chunks break off and disperse into the Chukchi Sea. In years with grounded ice offshore (thermal breakup), the nearshore ice is exposed to heat supplied by ocean and atmosphere for a longer period of time, leading to the most significant decay in ice under melt ponds. With significant decay under melt ponds, the adjacent stretches of level unponded ice are eventually advected parallel to the coast in response to dynamic forces. Once this ice...
is mobilized, the grounded ice breaks out as it continues to melt. The dynamic forces that trigger breakup could be either of a sporadic nature like a swell that overwhelms ice stability, or continuously present, eventually outgrowing ice strength as the ice weakens. Candidates for thermal decay of the ice are heat flux from ocean and atmosphere, surface meltwater, and radiation balance.

In all years of mechanical breakup, the average irradiance at breakup was comparatively high. Hence, there is some indication that, in addition to cumulative irradiance, higher mean irradiance may be conducive to mechanical breakup as it aids decay and ungrounding of stabilizing ridges [Mahoney et al., 2007b] and level ice. Barring knowledge of the grounding and stability of landfast ice, the irradiance trajectory of a given melt season (Figure 15) may serve as an indication of the likelihood of mechanical breakup.

5.2. Dynamic Forcing

We found that breakup is not associated with unusually strong winds. However, among the 3 years of highest

Figure 11. Ocean and weather data near UIC-NARL for the breakup season in 2010. Directions of currents and winds are the directions of movement toward and from, respectively. Sea level is given relative to mean lower low water (MLLW). Shaded areas highlight two notable breakout events (25 June and 8 July) and breakup (4 July).
wind speed during breakup were both mechanical breakup events that happened during easterly winds (2003, 2007). Hence, strong easterly winds (i.e., offshore winds) may be conducive to mechanical breakup.

[35] With the disproportional likelihood of observing westerly winds during breakup, wind fetch across the Chukchi Sea and resulting waves, swell, elevated sea level, and storm surges are candidate forces for breakup. While we have no measurements of waves and swell, wave action is known to be able to fracture ice in the marginal ice zone and landfast sea ice [Fox and Squire, 1991; Langhorne et al., 1998; Squire, 2007]. Elevated sea level was not observed during breakup in years we have data for (2009, 2010). However, following breakup in 2010, sea level was observed to be slightly elevated during a breakout event of grounded pressure ridges during easterly winds. This indicates the possibility that sea level changes may help dislodge grounded ice, which could facilitate mechanical breakup in years with only weakly grounded ridges.

[36] During thermal breakup, winds came from either easterly or westerly directions without a clear correlation between winds and ice drift. This lack of correlation is not surprising considering that radar observations of ice drift show that the potential influence of currents and winds on drift is of the same order of magnitude. Observed breakup could be delayed with respect to the stage of decay if motion is restricted in the direction of dynamic forces. However, melt in the nearshore region (e.g., 2006) and drift through passages in the discontinuous line of pressure ridges (e.g., 2008) do take place and reduce the practical importance of any restriction to the northeast or southwest of UIC-NARL.

Figure 12. ALOS AVNIR-2 false-color image at Barrow on 28 June 2010 (nadir-looking). Ice and clouds are bluish-white. B1 is the location of the mooring. Landfast ice has broken out within ~3 km of downtown Barrow.

Figure 13. Annual, cumulative melting degree days until breakup. Boldface years indicate thermal breakup.

Figure 14. Cumulative irradiance until observed breakup for different start dates of integration. Markers are the last digit of the year from 2000 to 2009, with A denoting 2010. Black markers are years of thermal breakup.

Figure 12. ALOS AVNIR-2 false-color image at Barrow on 28 June 2010 (nadir-looking). Ice and clouds are bluish-white. B1 is the location of the mooring. Landfast ice has broken out within ~3 km of downtown Barrow.

Figure 13. Annual, cumulative melting degree days until breakup. Boldface years indicate thermal breakup.

Figure 14. Cumulative irradiance until observed breakup for different start dates of integration. Markers are the last digit of the year from 2000 to 2009, with A denoting 2010. Black markers are years of thermal breakup.
Winds were not observed to come from the south and southeast during breakup, which is consistent with the general absence of winds from that direction.

5.3. Ice Decay

[37] There is agreement in magnitude between the range of accumulated melting degree days observed in years of thermal breakup at Barrow (i.e., 60 to 120 melting degree days) and the range reported by Barry et al. [1979] for the onset of ice movement in the Beaufort Sea (i.e., 55 to 140 melting degree days). The range reported by Bilello [1980] for the complete removal of ice at Resolute was higher (120 to 190 melting degree days), similar to the respective range reported by Barry et al. [1979]. In addition, the cumulative irradiance at breakup reported by Bilello [1980] (730 to 1050 MJ/m²) is of the same order of magnitude we found for thermal breakup (700 to 760 MJ/m²). Had we chosen a start date of integration on the basis of air temperature above 0°C, our values would have been higher. For example, we see from Figure 14 that a start day around 145 would have brought us into the same range as Bilello [1980], including both mechanical and thermal breakup events. Warm spells with partial snowmelt are common in Barrow around day 145 (25 May), leading us to conclude that irradiance observed by Bilello [1980] at Resolute is consistent with our observations at Barrow.

[38] Since sea ice temperature in the melt season is nearly isothermal [Petrich and Eicken, 2010], the conductive heat flux through the ice is small and the turbulent atmospheric heat flux and the oceanic heat flux will mostly contribute to

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**Figure 15.** Trajectories of cumulative irradiance versus average irradiance measured at the ARM site between 5 June and breakup.

**Figure 16.** Range of errors in breakup prediction for various integration start dates for years of thermal breakup (see Table 1).

**Figure 17.** Date of breakup forecast for 2009 versus initialization time of the WRF model. Circles indicate the expected breakup dates, and triangles indicate the end of a WRF forecast run without expected breakup. The vertical bars indicate the data source for the incoming shortwave flux (i.e., ARM measurements; green vertical bars) estimates on the basis of observed cloud cover (magenta vertical bars) and WRF runs (black vertical bars). The shaded horizontal bar indicates the range of thermal breakup dates in 2000–2008.
surface and bottom ablation, respectively, weakening the ice by reducing thickness. Irradiance is absorbed both near the surface and in the ice interior, contributing to decay and loss of strength by increasing porosity. For example, ice of 1.5 m thickness with porosity 0.9 and albedo 0.4 (melt ponds) would be completely melted by absorbing 690 MJ/m², a magnitude that could be realistically reached by the time of thermal breakup. Hence, we expect that ice under melt ponds has most likely melted by the time of thermal breakup. The potential contribution from turbulent atmospheric heat flux is smaller. In order to melt the example ice, assuming a surface temperature of 0°C and an ice–atmosphere heat transfer coefficient of 10 Wm⁻² K⁻¹, 480 melting degree days would be necessary, vastly exceeding the 80 and 62 melting degree days observed in 2001 and 2005, respectively. Hence, irradiance is the single most important contributor to decay leading to thermal breakup. However, considering mechanical breakup, average strength of landfast ice is more important and therefore ice thickness and melting degree days will have higher skill as indicators for the state of decay.

5.4. Forecast

Past approaches to predicting coastal ice breakup have mostly relied on melting-degree modeling as a measure of the total amount of heat supplied to melt ice, thereby structurally weakening and priming it for breakup [Bilello, 1980; Gudkovich, 1995]. Russian scientists have also developed empirical or statistical models that take into consideration wind speed and the local topography in predicting breakup dates [Gudkovich, 1995]. On the basis of melting degree days in Figure 13, we find that a threshold of 110°C days could be used as an indicator for breakup in 2000, 2006, 2008, and 2009. However, thermal breakup in 2001 and 2005, breakup in 2002 and mechanical breakup cannot be explained by this threshold alone. Also, the observed range of 60 to 120 melting degree days is too broad to be useful for forecasts, translating into the equivalent of ~10 to 14 days of uncertainty.

Given the prominent role that solar heating plays in ice decay [e.g., Perovich and Maykut, 1990], the spatial heterogeneity of a melting Arctic sea ice surface, and considering spatial heterogeneities in the surface air temperature field in coastal regions, the aforementioned spread in melting degree days is to be expected. Here, we took an approach employed in numerical sea ice models and advanced statistical models of glacier ablation by integrating measures of irradiance [Hock, 1999]. Data from Barrow indicate that thermal breakup occurred once a threshold in the cumulative irradiance recorded at the ARM site had been passed (700 MJ/m², starting integration at 5 June; cf. Figure 15). This relationship allowed for prediction of breakup in all years of thermal breakup. While the start date for the integration of shortwave flux was empirically set to 5 June, a time during which melt ponds are observed to proliferate along the coast of Barrow, the choice of start date is not critical if the threshold is adjusted accordingly.

We chose to operate the forecast with a fixed start date for all years, unlike the investigation by Bilello [1980] that started integration on the first day of temperatures above 0°C. At least at Barrow, both choices are arbitrary. Brief periods of temperatures above 0°C were observed as early as April (e.g., 2002, 2003, 2004, 2005, 2009), at a time of ice growth and increase in snow depth and clearly before the onset of appreciable melt. While temperatures above 0°C recorded at the Barrow airport have been associated with snowmelt on the tundra [Stone et al., 2002], there is currently no evidence of a correlation with melt pond development. Further, onset of melt pond development is a gradual process at Barrow, propagating south to north over the course of days to weeks. Hence, we chose to use a fixed date.

There is a degree of uncertainty in the forecast procedure as little account is taken for the initial ice conditions [cf. Gudkovich, 1995]. While ice thickness in May has been relatively constant throughout the years, we only consider the difference between grounded landfast ice (leading to thermal breakup) and ungrounded landfast ice (leading to mechanical breakup). Interannual variability of the degree of deformation and sediment entrained in the ice are not accounted for, both of which should affect absorption of light and melt pond development. Also, variability of snow depth and the timing of melt pond development are assumed invariants.

Considering only decay in the forecast we made an implicit assumption about dynamic forces. Decay is a continuous process while dynamic forces may either be continuous (e.g., winds, currents) or transient (e.g., winds, currents, swell, waves, tides, gusts). In the present breakup forecast we assumed that dynamic forces apply continuously. However, at least in 2008 when thermal breakup occurred at a time of changing wind direction, transient forces may have been important. The inclusion of dynamic forces into the prediction of breakup should improve forecast skill.

While 2 years is too short a time to reach definite conclusions about the skill of forecasts of springtime irradiance, the consistency in forecast breakup dates (Figure 17) suggests that systematic correlations might exist between forecast and observations at the comparatively long time scale of 2 weeks.

5.5. Definitions of Landfast Ice Breakup

We focused on one particular definition of breakup in section 4 on the basis of a physical process at one reference location in section 5.4. However, breakup has been defined differently to accommodate specific operational considerations or data limitations [e.g., Kniskern and Potocsky, 1965; Mahoney et al., 2007a].

An alternative definition may be based on observed community access to the sea from the Chukchi Sea coast. Independent of this study, records of Barrow community members are available on the first day of boating activity launched from the Chukchi Sea coast (C. George, personal communication, 2010). The boating records shown in Figure 8 indicate that the breakup process defined here in purely physical terms is associated with one of the key activities in the local community, access to the sea from the beach. In general, boating activity is observed around the same time as movement of nearshore ice. In years where boat access leads breakup at UIC-NARL, coastal ice broke up in stages from the south (near the residential areas of Barrow) to the north (at the reference point of this study). This is in particular the case for 2009 and 2010 where earlier breakup was observed right at downtown Barrow (Figure 12). In contrast, the comparatively delayed start of boating activity in 2006 resulted from a pronounced line of grounded pressure ridges that limited the possibilities for dispersal of
disintegrating nearshore ice and boat access further offshore (Figure 5).

[47] Differences in the dates of breakup and boating presented here may serve to illustrate that stages of the sea ice cycle are defined in relation to a specific purpose or use of the ice cover [Eicken et al., 2009]. While breakup in this study was defined to systematically investigate a physical process, this definition only approximates the requirements of boat access. Yet, within the limits discussed above, the consistently acquired set of physical observations can be used as indicator for conditions that are meaningful in a broader context.

5.6. Historical Accounts

[48] Sackinger and Rogers [1974] and Shapiro and Barnes [1991] documented breakup at UIC-NARL in the 1970s on the basis of imagery from a coastal X band radar. Their description mirrors our observations of 2006, with the largest ridge tracing the 20 m contour. They reported disintegration of the line of pressure ridges once the nearshore ice fractured into small floes and started to move. According to the detailed account of Sackinger and Rogers [1974] on ice breakup in 1973, nearshore ice did not start to move significantly until 22 July 1973, with pressure ridges completely drifted out on 3 August. By our definition, this breakup appears to have happened 11 days later than the latest breakup observed since the summer of 2000 (Table 1). The breakup process reported for the 1970s is consistent with thermal breakup, with the exception of the heavy ice year 1975 in which landfast ice remained along the shore throughout summer [Shapiro and Barnes, 1991].

[49] Our observations can be placed in historical context on the basis of observations of the U.S. Navy Hydrographic Office [1958]. Here, breakup is defined as the date the ice concentration decreases to 10% [Kniskern and Potokosky, 1965], which is similar to our record of the breakout of pressure ridges (Table 1). On the basis of a summary of 25 (unspecified) years of observation starting in the 1930s, according to their definition, breakup at Point Barrow happened at the earliest and latest on 15 June and 24 August, respectively, with an average given as 24 July [Kniskern and Potokosky, 1965]. Range and average compare well with the times of the disappearance of pressure ridges in Table 1, suggesting that both thermal and mechanical breakup used to occur at Barrow 50 to 80 years ago. However, noting that a typical time for the disappearance of pressure ridges would be around 15 July in our case (Table 1), it appears that grounded pressure ridges, when they formed, used to be either better anchored than they generally have been since 2000, or better protected from ocean swell by pack ice in the Chukchi Sea [U.S. Navy Hydrographic Office, 1958]. Ice conditions observed in 2006 are likely typical of this more traditional ice regime, as also noted by local ice experts (R. Glenn, personal communication, 2006).

6. Summary and Conclusion

[50] In this work we took the long-recognized and often repeated concept “breakup = ice decay + dynamic forces” literal and attempted to separate the decay process from the dynamic process. The novel aspect of this work is the combination of an in-depth investigation of the breakup process, previously limited to studies of one season, with an investigation of the predictability of breakup, which is limited to long-term studies. As a result, this appears to be one of the first studies of the interannual variability of the breakup process of landfast sea ice. Key insights gained include the value of discriminating two almost consecutive modes of decay of landfast ice (general weakening of the ice cover versus almost complete disintegration of ice under melt ponds), and the contribution of interannual variability of ice conditions (spatial confinement due to grounded ice) on the mode of decay relevant during breakup. While previous studies often considered breakup at multiple locations, the transferability of our results will still have to be tested. However, considering that both melting degree days and cumulative irradiance at breakup reported throughout the Alaskan and Canadian Arctic agree with our observations at Barrow, and considering that embayments may be sheltering landfast ice similarly to grounded ridges, our results are likely transferable. For example, investigating which of the two ice decay modes dominates at a particular location may guide the selection of indicators for breakup forecasts in the Canadian Arctic and elsewhere; for example, leading to the use of predominantly dynamic indicators in exposed areas and thermodynamic indicators in sheltered areas. Also, regions with low forecasting skill may turn out to exhibit a bimodal distribution of breakup modes similar to Barrow, a potentially helpful insight for forecasting. The suggested distinction between two breakup modes applies to ice forming melt ponds; that is, Arctic sea ice.

[51] We compared environmental conditions leading to breakup at Barrow from 2000 to 2010. While the reduction of ice thickness and internal weakening are important decay mechanisms for mechanical breakup, thermal breakup was preconditioned by the decay of ice under melt ponds. Breakup was observed disproportionally often during onshore (westerly) winds, leading us to suggest that oceanic forces like waves or swell may have contributed to breakup. Offshore (easterly) winds seemed to have to be strong for mechanical breakup to occur, indicating the importance of atmospheric forces. We found no evidence that strong currents or high tides are necessary for breakup during a rare coincident measurement of oceanic currents in 2010. Current reversal and speeds as high as 1 m/s were observed during separate breakout events a few days before and after breakup, respectively. The oceanographic measurements also show the increasing heat content of nearshore waters as a result of solar and possibly advective heating, both promoting thermal decay and breakup.

[52] This work highlights the importance of grounded pressure ridges for the stability of landfast sea ice in the Alaska Arctic, and the significant interannual variability of breakup dates observed during the past decade. Further, the study adds evidence to the fundamental importance of melt ponds in the breakup process. The nearshore environment allowed us to observe the transition from the commonly acknowledged preferential melt of melt ponds on a single piece of ice to agglomerates of ice floes with significantly larger cumulative perimeter, marking the beginning of a nonlinear, catastrophic disintegration of landfast ice driven by both lateral, top and bottom ablation.

[53] We have identified two physically distinct modes of breakup of landfast ice at Barrow over the past 11 years. Six
years of thermal breakup were characterized by significant melt in the nearshore zone in the presence of stabilizing pressure ridges, while in four years of mechanical breakup the landfast ice broke out in large pans with ice in less advanced stages of decay. One year (2002) exhibited characteristics of both thermal and mechanical breakup. On the basis of historical data, we inferred that both modes likely occurred between the 1930s and 1950s, and that breakup between 1973 and 1976 was likely thermal every year. While neither breakup mode is unheard of, we may add from eyewitness accounts of Barrow hunters that the prevalence of mechanical breakup in the recent decade is unusual on a 30 year time scale.

[54] We have compared two empirical measures for breakup progress, melting degree days and cumulative irradiance, and found cumulative irradiance to be the more precise indicator for thermal breakup of landfast sea ice at Barrow. The observed range in melting degree days until breakup at Barrow matches previous reports for the Beaufort Sea coast, leading us to conclude that the irradiance approach may be transferable along the Beaufort Sea coast and possibly also along the east coast of the Chukchi Sea.

[55] On the basis of 2 years of breakup forecasts, it appears that the timing of thermal breakup can be gauged 2 weeks in advance on a three tiered scale of “early,” “average” and “late.” Future work on timing and variability of landfast ice breakup should record the breakup mode to guide the development of location-specific ice forecasts.

Appendix A

[56] Below follows a description of the breakup process at UIC-NARL, 5 km NE of Barrow, Alaska, for the years 2000–2010. Descriptions are based on data from web cam (w/c), Landsat (L/S), AVNIR-2 (A) or MODIS (M) imagery, RADARSAT (R/S) or ERS-2 (E), and coastal radar (c/r).

A1. Thermal Breakup on 10 July 2000

[57] Nearshore ice moved briefly during three discrete events prior to breakup. An ice shove took place on 26 June (w/c), and slight, momentary southbound movement of ice close to the shore was observed on both 2 July and 5 July (w/c). Starting 10 July, nearshore ice movement was continuously southbound (w/c), defining breakup. The line of pressure ridges started to disintegrate from 18 June (w/c). In this configuration, surface melt of the nearshore ice progressed and the nearshore ice began to drift south on 30 June (w/c). The coastal lead opened on 10 July, followed by the disappearance and melt of remaining pressure ridges by 16 July (w/c). On the basis of ARM data, 2002 exhibited a significant reduction of tundra albedo by 25 May, 1 to 2 weeks earlier than in other years since 2000. Hence, large-scale surface melt, including melt on sea ice, may have followed an unusual trajectory in 2002. Breakup happened on 30 June when winds sustained 15 knots from W.

A2. Thermal Breakup on 5 July 2001

[58] Apart from an ice shove on 19 June (w/c), landfast ice was stationary until nearshore ice started to move south on 5 July (w/c). The remaining ice moved out on 7 July (w/c). Breakup happened during 10 knot winds from NW.


[59] Undeformed landfast ice remained in place without being stabilized by pressure ridges throughout winter, showing the same extent on 19 March 2002 as it did on 21 October 2001 (w/c). Grounded pressure ridges formed in March offshore and detached from this ice, allowing the open water between pressure ridges and landfast ice to freeze. This young landfast ice was presumably blown out between 4 and 7 June (w/c). Until 19 June, the Chukchi Sea lead opened and closed several times seaward of the pressure ridges. Ice was observed to drift southbound through the space between nearshore ice and pressure ridges on 15 June (w/c). Further, the line of pressure ridges started to disintegrate from 18 June (w/c). Chukchi Sea ice pushed toward the shore past the remaining grounded ridges up to the nearshore ice on 19 June (w/c). In this configuration, surface melt of the nearshore ice progressed and the nearshore ice began to drift south on 30 June (w/c). The coastal lead opened on 10 July, followed by the disappearance and melt of remaining pressure ridges by 16 July (w/c). On the basis of ARM data, 2002 exhibited a significant reduction of tundra albedo by 25 May, 1 to 2 weeks earlier than in other years since 2000. Hence, large-scale surface melt, including melt on sea ice, may have followed an unusual trajectory in 2002. Breakup happened on 30 June when winds sustained 15 knots from W.


[60] After a large chunk of landfast ice broke out south of UIC-NARL on 24 June (M), seaward deformed landfast ice broke out on 24 June (w/c) (breakup), followed by the remaining nearshore level ice on 25 June (w/c). Breakup happened during 10 to 15 knot winds from E.

A5. Mechanical Breakup on 18 June 2004

[61] Coastal ice from several kilometers north of UIC-NARL to several kilometers south of Barrow broke out at once from 18 to 19 June (c/r, M) (breakup), Breakup happened during 10 to 15 knot winds from SW.

A6. Thermal Breakup on 8 July 2005

[62] Breakup started after landfast sea ice broke out in the Beaufort Sea NE of Point Barrow on 7 July (M), followed by breakup of the ice immediately north of UIC-NARL on 8 July (R). The nearshore landfast sea ice started to drift out to the north at midnight 8 July (w/c), defining breakup. Pressure ridges broke out on 13 July. Breakup happened during westerly winds between 0 and 15 knots, following 4 h of winds from SE between 20 and 25 knots.

A7. Thermal Breakup on 6 July 2006

[63] Nearshore ice was confined by grounded pressure ridges along the Chukchi Sea coast. Within this confinement, nearshore ice moved along the coast between 3 July and 24 July (M), with breakup (southbound movement) first detected at NARL on 6 July (c/r). Ice drift in the coastal lead was southbound during breakup (c/r). Pressure ridges broke out starting 3 August, and the coast was ice free by 9 August (M, c/r). Breakup happened during 10 to 15 knot winds from NE.

A8. Mechanical Breakup on 27 June 2007

[64] After the landfast ice broke out south of Barrow on 20 June (M), breakup was observed at downtown Barrow.
and Browerville on 21 and 23 June, respectively (c/r). Landfast ice broke out at UIC-NARL on 27 June (c/r) (breakup). Only one ice island remained at Browerville and eventually broke out on 2 July (M, c/r). Breakup happened during 15 to 20 knot winds from E.

A9. Thermal Breakup on 8 July 2008

With the Chukchi Sea coast heavily ice covered, landfast ice in the Beaufort Sea NE of Point Barrow began to break out around 5 July. Breakup at UIC-NARL occurred on 8 July with northbound movement of nearshore ice along the coast north of Barrow (c/r, A). Breakup at downtown Barrow did not occur until 13 July. Pressure ridges broke out between 17 and 20 July (c/r). Ice drift in the coastal lead was northbound during breakup (c/r). Breakup occurred while winds decreased from 15 to 10 knots and changed from E to NW.

A10. Thermal Breakup on 11 July 2009

Landfast ice was still well in place north of Browerville on 7 July (M). At UIC-NARL, nearshore ice was still present on 9 July, held in place by grounded ridges between Barrow and Point Barrow (E). The nearshore ice was gone by 12 July (M), and grounded ridges gradually broke out or melted until the coast was ice free by 18 July (M). Breakup occurred with winds of 10 knots from SW. Ice drift in the coastal lead was northbound during breakup (c/r). Breakup happened while winds decreased from 15 to 10 knots and changed from E to NW.

A11. Mechanical Breakup on 4 July 2010

Coastal ice broke out in segments including both nearshore ice and pressure ridges. Breakout took place at downtown Barrow on 25 June (c/r, w/c) (cf. Figure 12), from downtown Barrow to UIC-NARL on 4 July (c/r, M) (breakup), and north of UIC-NARL up to Point Barrow on 8 July (M, c/r). Some ridged ice remained between UIC-NARL and Point Barrow to break out on 9 July (M). During breakup, winds changed from E to W and N at 10 to 15 knots. Oceanographic measurements are shown in Figure 11 and described in section 4.2.

Appendix B

B1. Forecast Irradiance

Our investigations with ARM measurements show that the WRF forecasted irradiance is biased. In order to improve the irradiance forecast we apply an empirical correction as outlined below.

Assuming clouds are conservative scatterers, the fractional downwelling irradiance under a cloud cover is

$$\frac{F_1}{F_0} = \frac{1 - \alpha_c}{1 - \alpha_g \alpha_c},$$

where $F_1$ is the downwelling irradiance near ground level, $F_0$ is the clear sky irradiance, $\alpha_g$ is the ground albedo, and $\alpha_c$ is the effective (cloud cover averaged) cloud albedo.

We calculate the fractional downwelling irradiance of the WRF model from

$$f = \frac{F_{WRF}}{F_{est}},$$

where $F_{WRF}$ is the downwelling flux produced by the forecast, and $F_{est}$ is the estimated clear sky flux outlined in equations (B5)-(B7). Inverting equation (B1) and adding an offset, we obtain the effective cloud albedo from

$$\alpha_c = \frac{1 - f}{1 - \alpha_{WRF}} + \alpha_{corr},$$

where $\alpha_{WRF}$ is the assumed ground albedo of the WRF model and $\alpha_{corr}$ is an empirical cloud albedo offset.

With the actual ground albedo at the ARM site $\alpha_{ARM}$, we calculate the downwelling forecast irradiance

$$F_{est}^F = \frac{F_{est}}{1 - \frac{\alpha_g - \alpha_{ARM}}{\alpha_g}},$$

The parameters used for the irradiance correction are: $\alpha_{ARM}$ is 0.6 and 0.2 before and after observed snowmelt, respectively, $\alpha_{WRF}$ is 0.65 and 0.2 if the ground in the WRF model is ice covered and ice free, respectively, and the offset $\alpha_{corr} = 0.1$.

On the basis of comparison with ARM data, the clear sky irradiance $F_{est}^0$ at Barrow in June and July is estimated on the basis of the solar zenith angle $Z$ from

$$F_{est}^0 = \Psi I_0 \cos(Z),$$

where

$$\cos(Z) = \cos(h) \cos(\delta) \cos(\Phi) + \sin(\delta) \sin(\Phi)$$

and

$$\delta = -23.45^\circ \cos(360^\circ(j + 10)/365).$$

Here, $h$ is the local hour angle (0 at noon, 180° at midnight), $\Phi$ is the latitude, $j$ is the day of the year, $I_0 = 1368$ Wm$^{-2}$ is the solar constant, and $\Psi = 0.78$ is a calibration constant. If $\cos(Z) < 0$ then $F_{est}^0$ is set to 0.

B2. Irradiance Estimate

Owing to the delay of the availability of ARM data, the downwelling shortwave flux is estimated from METAR cloud and visibility records. Using equation (B4), the effective cloud albedo is estimated with the following empirical approach.

$$\alpha_c = \max[0.2, (0.5 + 0.1 g)\alpha],$$

where $\alpha$ is the effective cloud coverage and $g$ is a weight factor. We set $g = 0$ unless the cloud ceiling is below 2000 ft and the sky condition is either OVC (overcast) or VV (vertical visibility). If the cloud ceiling is below 2000 ft and the sky condition is either OVC or VV, $g = 1.5$ if the visibility is at least 3 miles, and $g = 5$ if the visibility is less than 3 miles.
The cloud coverage \( c_c \) is calculated assuming random overlap of individual cloud layers, \( i \), specified in the METAR report. Specifically,

\[
c_c = 1 - \prod_{i} (1 - c_{ci}),
\]

where index \( i \) enumerates the cloud layers, and \( c_{ci} \) is 0, 0.125, 0.375, 0.625 and 1.0 for sky conditions CLR (clear skies), FEW (few clouds), SCT (scattered clouds), BKN (broken cloud cover), and either OVC (overcast) or VV (vertical cloud thickness), respectively. However, above factor \( c_{ci} \) is reduced by 20% if the ceiling height of layer \( i \) is less than 1000 ft.

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