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Landfast sea ice extent in the Chukchi and Beaufort Seas: The annual cycle and decadal variability

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ABSTRACT

Through analysis of over 2500 synthetic aperture radar (SAR) scenes spanning the period 1996–2008, we have compiled the most comprehensive dataset to date on landfast sea ice extent and its annual cycle in the Chukchi and Beaufort Seas. Our results show that landfast ice in the central and western Beaufort Sea forms earlier, breaks up later, occupies deeper water and extends further from shore than that in the Chukchi Sea. The differences in the timing of the annual landfast ice cycle are largely due to regional contrasts in the southward advance of pack ice in early winter and the onset of spring thaw. On the other hand, we suggest that the differences in landfast ice extent between the two seas are related to the number and distribution of recurring grounded ice features. These grounded features appear as "nodes" where the seaward landfast ice edge (SLIE) persistently recurs in multiple years. In the Beaufort Sea there are several such nodes that occur in water depths around 20 m, giving rise to the similarity between the average SLIE location and the 20 m isobath. We attribute the narrower landfast ice in the Chukchi Sea and lack of a consistent relationship with bathymetry to the sparsity of nodes in the Chukchi Sea. In comparing our results with data from the period 1973–76, we find that landfast ice extent in the Beaufort Sea has not changed significantly in the last four decades. However, in the Chukchi Sea our results show the landfast ice width has decreased by a coast-wide average of 13 km over this period. We again attribute this difference between the two seas to the distribution of recurring grounded ice features. Over the 12 annual cycles in the study period, we identify trends indicating that landfast ice is forming later and disappearing earlier by approximately one week per decade. Although these trends are not statistically significant, they are in agreement with an overall shortening of the landfast ice season by as much as two months over the past three decades, revealed by a comparison with earlier findings for the period 1973–77.

1. Introduction and background

1.1. Overview

The Arctic Ocean region is currently undergoing significant, environmental and socio-economic change (Perovich, 2011). Summer minimum sea-ice extent has been subject to an average reduction of more than 10% per decade since 1979, with recent reductions faster than predicted by many climate models (Stroeve et al., 2012), and a near-complete loss of summer ice projected by the late 2030s (e.g., Wang and Overland, 2009, 2012). Observations and projections of summer ice retreat rates are highest for the western Arctic, specifically the East Siberian, Chukchi and Beaufort Seas (Comiso, 2002; Douglas, 2010; Hutchings and Rigor, 2012).

Partly as a result of these observed and predicted changes, marine traffic and activities related to offshore oil and gas development have grown substantially over the past decade and are projected to increase further (Arctic Council, 2009; Brigham, 2011). This will create new societal and ecological risks. Commercial activities in areas of critical habitat may place greater stress on marine mammals already considered threatened by loss of habitat due to retreating sea ice (U.S. Fish and Wildlife Service, 2008). At the same time, increased maritime activity in this changing and remote region will generate new challenges for maritime and environmental security.

While there are few if any systematic direct observations of the extent and impacts of these changes in the Alaska coastal zone and inner-shelf waters, native communities have reported for some time about substantial changes in the sea-ice regime, including later onset of ice formation and a less stable and less predictable ice cover (Gearheard et al., 2006; George et al., 2004; Huntington, 2000; Kapsch et al., 2010; Krupnik and Jolly, 2002). Given the importance of Alaska coastal and inner-shelf waters from an ecological, economic and sociological perspective, in particular in the light of recent sales of offshore oil and gas leases, there is a clear need for information on the current status of the coastal sea ice regime. In a previous similar study,

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Mahoney et al. (2007a) found evidence that landfast ice along Alaska's northern coast formed later and broke up earlier during the period 1996–2004 than it did during the 1970s. Here, we build on this work to present a comprehensive analysis of recent landfast sea ice extent and variability in the Chukchi and Beaufort Seas during the 12 "ice seasons" between 1996 and 2008.

1.2. Sea ice conditions in the Chukchi and Beaufort Seas

The Chukchi and Beaufort Seas lie north of Alaska and together contain the entire US Arctic domain, but are also bounded by Russian and Canadian coasts, respectively. Differences in bathymetry, ocean circulation, latitude, the alignment of the coast and prevailing wind direction all contribute to creating different sea ice regimes in the two seas. The Chukchi Sea is dominated by a broad, shallow shelf (the Chukchi Shelf) mostly less than 50 m deep with shoals such as Hanna Shoal and Herald Shoal rising to around 20 m. Conversely, water shallower than 50 m in the Beaufort Sea occupies only a narrow coastal strip less than 100 km wide. Most of the Beaufort Sea is more than 1000 m deep and is part of the Canada Basin. Sea ice motion in the Beaufort Sea is dominated by the clockwise rotation of the Beaufort Gyre, which is driven by atmospheric circulation around a persistent region of high atmospheric pressure (the Beaufort High). In winter the average drift along Alaska's northern coast is roughly shore-parallel. This pattern of motion brings old multiyear ice into the Beaufort Sea from the region north of Canada, where the oldest and thickest ice in the Arctic is found. By comparison, the Chukchi Sea is mostly devoid of multiyear sea ice and surface winds are more variable. Moreover, the configuration of the coastline is such that whichever direction the sea ice drifts, it will be moving toward or away from some section of coast. This means that open water is almost always being created in the Chukchi Sea, even in winter. Such open water is created in leads, which are linear openings in the ice formed either between floes or at the coast. The prevailing winds in the northern Chukchi Sea create a semi-persistent flaw lead along the Alaska coast, which provides crucial habitat and migratory pathways for marine mammals.

1.3. Geophysical, ecological and societal importance of landfast sea ice

Landfast sea ice, also referred to as shorefast or simply "fast" ice, is defined according to the World Meteorological Organization, 1970 as "ice which remains attached to the coast". As such, it forms a rigid, immobile boundary that occupies the triple juxtaposition between the ocean, land and atmosphere, where it buffers the coast against the erosive action of waves (Lantuit and Pollard, 2008) and plays an important role in sediment dynamics (Eicken et al., 2005b). By effectively isolating the coastal ocean from the atmosphere, landfast ice also affects the fate of river inflow when it enters the marine environment (Kasper, 2010).

The seaward landfast ice edge (SLIE) is marked by either open water or drifting pack ice. As a result, landfast ice provides important habitat for ringed seals and polar bears providing them with ideal denning locations in proximity to prey (Laidre et al., 2008). The SLIE is also the landward edge of coastal polynyas, which are important regions of dense water production (Weingartner et al., 1998) and new ice formation. As an extension of the land, landfast ice is used as a hunting and traveling platform by Arctic coastal communities (e.g., Gearheard et al., 2006; Krupnik, 2010) and for the construction of ice roads (Masterson, 2009; Potter et al., 1981) and runways. The presence and stability of landfast ice in Alaska are therefore of considerable economic importance for offshore oil and gas development (Eicken et al., 2009) as well as for identifying the seasonal availability of potential ports of refuge for maritime activities (CRRC, 2009). The extent and thickness of landfast ice was also a critical consideration during the recent wintertime delivery of fuel to the City of Nome in January 2012.

1.4. Formation and development of Arctic landfast ice

Although stationary by definition, landfast ice is formed and deformed by a combination of dynamic and thermodynamic processes, each with distinct annual cycles and geographic variations in predominance. Consequently, the extent and appearance of landfast ice differs significantly between regions of the Arctic. In much of the Russian Arctic, the landfast ice extends tens to hundreds of kilometers from the coast (Barnett, 1991; Eicken et al., 2005a; Zubov, 1945) which is one or two orders of magnitude greater than the typical width of landfast ice in the Chukchi and Beaufort Seas (Barry et al., 1979; Mahoney et al., 2007a; Stringer et al., 1980). Such basin-scale differences in spatial extent are related to differences in nearshore bathymetry and contrasts in ice dynamics. However, we are not aware of any Arctic-wide relationship between the water depth and the location of the landfast ice edge. Among the different water depths that have been cited as the limits of landfast ice extent are 25 m along the Siberian coast (Barry et al., 1979; Zubov, 1945), 10 m in the Kara Sea (Barry et al., 1979; Divine et al., 2004); between 18 m and 30 m in the Beaufort Sea (Canadian Hydrographic Service, 1968; Kovacs, 1976; Kovacs and Mellor, 1974; Mahoney et al., 2007a; Reimnitz and Barnes, 1974; Shapiro, 1975; Stringer, 1974; Stringer et al., 1980; Weeks et al., 1977), 100 m near Severnaya Zemlya (Divine et al., 2004) and 180 m off the eastern coast of Baffin Island (Jacobs et al., 1975).

In the Chukchi and Beaufort Seas, landfast sea ice is a seasonal phenomenon. The annual landfast ice cycle can be broadly characterized by a gradual seaward advance from the coast beginning in late fall or early winter (October–November) followed by a rapid retreat coinciding with the onset of spring (May–June). The range of dates is due to geographic differences in the arrival of the seasons as well as interannual variability in the behavior of the landfast ice. Landfast ice forms first in lagoons and sheltered embayments. To extend into deeper water and remain stable, landfast sea ice in the study area must be anchored by grounded ridges (Mahoney et al., 2007b), which partly explains the relationship between extent and bathymetry. The formation of such ridges limits the timing of stabilization as ridges formed from thin, young ice tend to have shallower keels than ridges created from thicker ice (Amundrud et al., 2004). In an earlier study, Mahoney et al. (2007a) found that during the period 1996–2004, landfast ice in northern Alaska formed later and broke up earlier than it did during the1970s (Barry et al., 1979).

2. Datasets and methods

2.1. Definition of landfast ice from remote sensing data

A detailed summary of different definitions of landfast ice and their applicability to remote sensing data is provided by Mahoney et al. (2006) and Eicken et al. (2006). The definition used here is the same as that used by Mahoney et al. (2007a) and combines two criteria that distinguish landfast sea ice from drifting sea ice:

1. The sea ice is contiguous with the shoreline.
2. The sea ice lacks motion detectable in satellite imagery (at a scale of a few hundreds of meters) for approximately 20 days or more.

We note that unlike definitions used in operational datasets such as the ice charts produced by the National Ice Center, our definition does not rely on the presence of a flaw lead and uses no remote-sensing signatures or textures of sea ice, other than to distinguish it from open water. The time period of 20 days was chosen to be short enough to capture both the annual cycle of advance and retreat as well as the higher frequency variability due to stable extensions and breakouts. It also spans more than a single synoptic period and so precludes sea ice that merely comes to rest temporarily and lacks a mechanism to hold it fast against offshore or alongshore forcing. In keeping with the