DEFINING AND LOCATING THE SEAWARD LANDFAST ICE EDGE IN NORTHERN ALASKA

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ABSTRACT

The seaward landfast ice edge (SLIE) is simple to define conceptually but more difficult to determine in practice, partly since both the location and a lack of motion must be determined over time, implying that a single observation is insufficient. We examine different definitions of landfast ice used by others and then propose our own, consisting of two criteria: 1) the ice is contiguous with the land, and 2) the ice lacks detectable motion for approximately 20 days.

This definition is applied to a time series of Radarsat synthetic aperture radar (SAR) imagery of the northern Alaska coast. Analysis reveals the presence of nodes where the SLIE exists more frequently. Nodes occur near the 20m isobath, suggesting grounding helps stabilize the SLIE in these locations. Comparison with studies from the 1970's suggests a that the stable extent of landfast sea ice has changed very little. Further work will carried out to determine whether there has been any change in the annual cycle. We also note that any comparisons must take into account relevant definitions and methods. This is particularly so with operational datasets that lack the benefit of hindsight such as the National Ice Center Ice Charts, which can differ significantly from our own for the same time period.

INTRODUCTION

Landfast sea ice is the largely stationary ice attached to the coasts of ice-covered seas. It is an integral component of the arctic environment and is of great importance to coastal communities, where it is used as an extension of the land for travel and to hunt marine mammals that are associated with the landfast ice and the adjacent system of leads. Nearshore oil and gas development in the Arctic also relies on the landfast ice as a stable platform. Landfast ice also reduces the effects of coastal erosion.

Along the Alaskan Arctic coast, landfast ice is a seasonal phenomenon between typically ice-free summers. Starting around late fall, it undergoes a gradual increase in area towards a stable extent before it experiences a rapid break-up and retreat in spring. Sea ice ridges with keels deep enough to become grounded play an important role in anchoring the landfast ice. Consequently, the location at which the seaward landfast ice edge (SLIE) becomes stable is dependent upon the severity of ridging (Tucker *et al*., 1978; Stringer *et al*., 1980) and the local configuration of coast and bathymetry (Reimnitz *et al*., 1978). It is widely noted that the landfast ice edge in the Beaufort Sea coincides with the 20m isobath (Barry, *et al*. 1979; Kovacs, 1976; Stringer *et al*., 1978).

DEFINITION OF LANDFAST SEA ICE

Numerous definitions of landfast ice can be found in the literature, which differ according to the processes considered relevant to a particular study. According to Weaver (1951), “fast ice or landfast ice is the young coastal ice which, in stationary sheets, builds seaward from the shore of landmasses … by being more or less attached to the shore, or by being otherwise confined”. The World Meteorological Organization (WMO, 1970) defines fast ice as “Sea ice which remains fast along the coast, where it is attached to the shore, to an ice wall, to an ice front, or over shoals, or between grounded icebergs”. Stringer *et al*. (1978) describe the fast ice zone as ‘the area generally shoreward of the 20m isobath with quite stable ice much of the year’ and only include ice contiguous with the shore. Barry *et al*. (1979) list three criteria that can distinguish landfast ice from other forms of sea ice: ‘(i) the ice remains relatively immobile near the shore for a specified time interval; (ii) the ice extends from the coast as a continuous sheet; (iii) the ice is grounded or forms a continuous sheet which is bounded at the seaward edge by an intermittent or nearly continuous zone of grounded ridges’. In 1980, Stringer *et al.* use the term “contiguous ice” synonymously with “fast ice” as described by the WMO. Zubov (1945) does not give a definition of what he calls fast ice, but instead describes the conditions that favor its growth from coastlines and islands. Grounded ridges are not mentioned, although thickening through rafting is, which probably reflects the different physical regime under which landfast ice in the Russian Arctic forms.

These definitions and descriptions all agree that landfast ice (or fast ice) is adjacent to the coast and characterized by a lack of motion, although none explicitly specify a time interval over which this must occur. Furthermore, as will be discussed in detail below, it is generally not possible to identify sea ice that is grounded or otherwise anchored from remotely sensed data. However, it is possible to identify sea ice that is both stationary and contiguous with the coast. In the context of this paper we will limit the definition of landfast sea ice to these criteria:

1) the ice is contiguous with the land

2) the ice lacks detectable motion for approximately 20 days.

Stringer *et al*. (1978; 1980) and Barry *et al*. (1978; 1979) used similar criteria where overlap was available between consecutive Landfast scenes allowing them determine a lack of motion over a time period of between 1 and 4 days. Where no overlap occurred however, the flaw lead or edge of the contiguous ice was used instead. The National Ice Center (NIC) adopt a similar definition when comparing a variety of remote sensing products to produce weekly ice charts. However, their primary criterion is uniformity of color (in visible range imagery) or texture (in microwave or infra-red imagery) shoreward of a clearly-defined edge (J. Pena, personal communication, 2005). We must also stress that our definition is one that can only be applied retrospectively and so our results will be inherently different to operational datasets such as the NIC ice charts.

Our definition uses no flaw lead or textural information and employs a longer time period that was deemed geophysically meaningful and appropriate for nearshore operations in ice-covered waters. It is 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.

REMOTE SENSING OF LANDFAST SEA ICE

Owing to the broad extent of landfast ice along coastlines where access is difficult, remote sensing offers an ideal way to observe its annual cycle. Landsat I and II channel 7 (0.8 – 1.1 μm) data were used in an extensive series of studies of Alaska's landfast ice during the 1970's prior to leasing parts of the continental shelf for oil exploration (Barry *et al*., 1979; Stringer *et al*., 1978, Stringer *et al*., 1980). The high resolution (80m) near-infrared images allowed identification of sea ice that was contiguous with the coast with sufficient detail to be able to detect small-scale motion. However, due to the darkness of the polar winter, the studies were focused on the landfast ice extent from February to early spring and the subsequent decay process. The repeat interval between orbits was 18 days, but at the latitude of the northern Alaskan coast, overlap between orbits allowed regions of the coast to be covered on up to 4 consecutive days.

Radarsat synthetic aperture radar (SAR) data from the Alaska Satellite Facility provides imagery of Earth's surface independent of clouds and darkness. The moderate resolution ScanSAR data has a repeat interval of approximately 3 days and a pixel size of 150 m and pixel spacing of 100 m and so is capable of detecting features and motion of a similar scale to those identified in Landsat images. However, there are a number of processes not associated with detectable motion that can lead to a change in the backscatter over time, which make the identification of stationary ice more difficult. Different incidence angles between orbits can cause this, but the sea ice itself also evolves and this, in turn, alters the radar interaction with the ice thereby resulting in a different backscatter coefficient.

Frost flowers on newly formed sea ice can generate the strongest backscatter (Onstott, 1992), though wind or snow on the surface soon dampen their effect. Once formed, sea ice desalinates over time (Weeks and Ackley, 1986). As a result, the radar energy penetrates more deeply, which leads to an increase in backscatter. Deformation of level ice increases the surface roughness and also the backscatter coefficient (Hallikainen and Winebrenner, 1992). It should be noted that the term roughness is used in relation to the radar wavelength. Hence small-scale height variations on the sea ice can yield a similar backscatter coefficient to large ridge fields, which contain both large- and small-scale roughness. Fetterer *et al.* (1994) find that new ice and open water can exhibit a wide range of backscatter coefficients since the surfaces of both can be very smooth or roughened by small-scale ice deformation or wind-induced waves.

The strongest changes in backscatter of landfast ice occur at the end of the sea ice season and are associated with warming and melting of the ice and snow. Holt and Digby (1984) combined field observations of the evolution of the ice and snow cover with space borne and airborne SAR measurements and describe processes that lead to rapid fluctuations in backscatter over landfast ice during the melt period. The production of superimposed ice nodules in the snow early in the spring, followed by flooding and then draining of the ice surface can lead to an increase in the backscatter, followed by a sudden decrease and then another increase (Barber *et al.*, 1995).

By its coastal nature, landfast ice can be influenced by rivers where they meet the sea. The freshwater reduces the salinity of the seawater near the mouth of the river and therefore the bulk salinity of ice that forms from it. This increases the penetration depth and allows scattering from the ice-water interface leading to a high backscatter coefficient. Where the water is shallow enough however, the ice can freeze to the bed, whereupon there is no ice-water interface and the dielectric contrast at the bottom of the bed is greatly reduced. This leads to a sudden reduction in the backscatter, which allows identification of the bottom fast ice zone (Eicken *et al.*, 2005; Solomon *et al.*, 2004). In the spring, the river water floods the landfast ice, reducing the backscatter coefficient to that of calm open water. Early in this process it can be seen that the ice beyond the flooded area remains stable and is still contiguous with the coast. However, later in process, near larger rivers, such as the Mackenzie in Canada, the flooded area can be so extensive that it becomes difficult to determine whether the ice beyond can still be classified as landfast. The effect is an underestimate of landfast ice extent and overestimate of the stage of decay in these areas.

METHOD

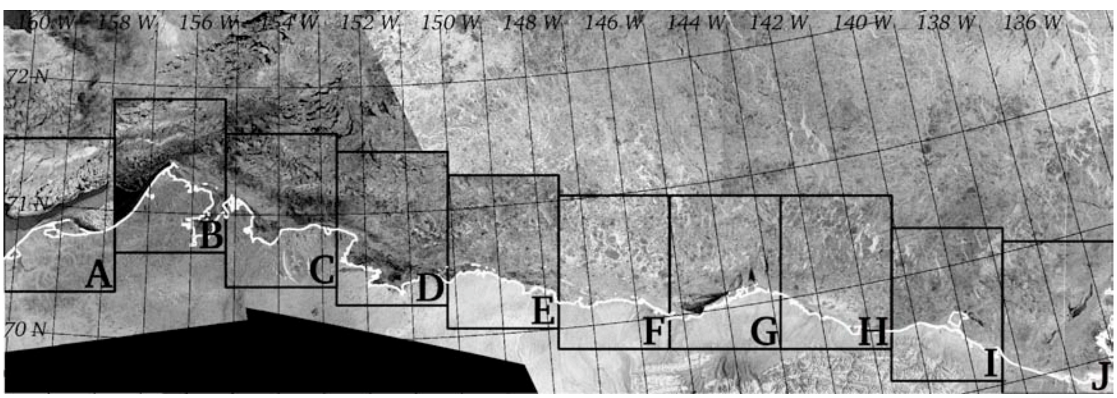

Figure 1 The full extent (955 × 330 km) of the study area shown by a mosaic of 4 parent Radarsat scenes. Also shown are the (95.5 × 132 km) subregion boundaries. Note that the subregions are cropped from the parent scenes so that they do not contain any mosaicking edges. SAR imagery © Canadian Space Agency (2002)

Study area and subregions

The study area is shown in Figure 1. It measures 955 km by 330 km in an Albers equal area projection such that at its center point its axes are aligned east-west and north-south. Mosaicked SAR imagery is cropped to fit this rectangle. Within the study area are 10 subregions (Figure 1), each measuring 95.5 km by 132 km and chosen such that it can be almost wholly taken from a single parent image leaving it free of mosaicking artifacts. The importance of this is explained below.

Data assimilation

Moderate resolution Radarsat ScanSAR wide beam data were ordered via the Alaska Satellite Facility (ASF) electronic data gateway and were chosen to provide complete coverage of the study area approximately every 10 days. The data were made available in GeoTIFF format by the ASF Advanced Product Design group with a geolocation accuracy stated to be 5 pixels or 500m. Each image covers an area 550 km by 550 km and is one of a group of parent scenes for a mosaic cropped to the study area. Each mosaic is made up of between 3 and 5 parent scenes separated in time by between 2 and 4 days. Approximately 1000 parent scenes were used to create 238 mosaics during the 8-year study period

Prior to any landfast ice analysis in the images, the data were checked to ensure adequate coverage of the study area and each subregion. In addition, scenes with a large geolocation error were identified and either corrected with a simple horizontal translation or removed from the dataset. The stated geolocation accuracy could give rise to colocation errors of up to 10 pixels or 1 km between parts of two mosaics, though where possible this was reduced to less than 500 m.

Delineation of landfast ice from consecutive SAR mosaics

Initially, it was thought that our two defining criteria could be applied to SAR data in an automated fashion to define the SLIE from consecutive colocated imagery, despite the processes discussed above, which lead to changes in the backscatter over time. These processes act least strongly on ridges and areas of deformed ice and so a technique was developed to detect edges and their orientation, looking for changes between mosaics. This technique is discussed by Mahoney *et al*. (2004) and involves calculating the vector grayscale gradient fields of 3 colocated SAR images and finding the magnitude of the net difference between them. The parent scenes had sufficient overlap that the process was carried out on subregions that were free from mosaicking edges, which contribute artificial gradients (Figure 1). Automated delineation from these gradient difference images proved successful during mid-winter when the SAR backscatter from landfast sea ice is most stable, but manual examination in conjunction with the parent SAR imagery was required at other times. For consistency, the SLIE was delineated at all times of year through detailed manual examination of 3 consecutive SAR mosaics and the derived gradient difference image.

Due to irregularities in the availability of data, the time period spanned by consecutive mosaics is not constant between mosaics pairs. It is not even constant between different parts of a mosaic pair due to the time span between groups of parent images. It is therefore not possible to state an exact time period over which the ice exhibits no detectable motion, but the average time period spanned by three consecutive mosaics is 19.7 days. This is not likely to contribute to a significant error in the SLIE position at any particular place or time or in the overall distribution of SLIEs over an entire year. However, it is possible that the SLIEs identified in different regions of the study area for a given period belong to different SLIEs that occurred during that time. This is unlikely to greatly affect the analysis that follows, but it is a cautionary note on interpreting individual SLIEs.

RESULTS

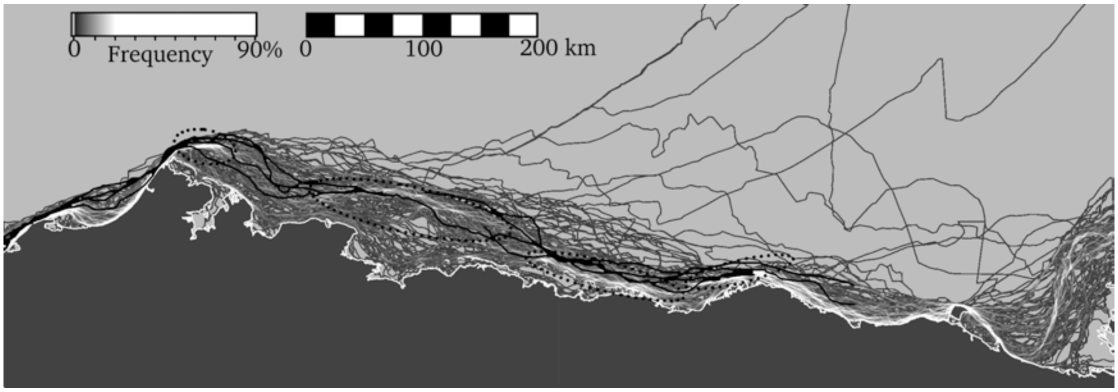

Figure 2. All 222 SLIEs stacked so that the grey value of a line indicates the relative frequency with which the SLIE occurred at that point during the 8-year study period. A white zone of preferred occupation is evident, within which are discrete nodes where the SLIE is more stable. The black lines are the spring-summer positions of the landfast ice edge determined by Barry *et al.* (1979). The dotted ellipses indicate the locations of nodes.

As described above, SLIEs were delineated using a combination of 3 consecutive Radarsat mosaics and the corresponding gradient difference mosaics. Consequently, for each season, there were 2 fewer SLIEs identified than there were mosaics available. Figure 2 shows the position of all the SLIEs for all 8 seasons. The lines representing the SLIEs were widened to 1 km and then stacked so that the value at a point, indicated by its color, represents the relative frequency with which a SLIE occurred at that location and can be viewed as a measure of SLIE stability. When all the SLIEs are combined in this fashion, a zone of preferred locations is readily apparent, within which are nodes of greater stability. The locations of the nodes are indicated by the dotted ellipses in Figure 2 and the likely processes responsible for their existence are discussed below.

The landfast ice areas for each delineated SLIE are stacked in a similar fashion in Figure 3 for each of the 8 seasons in the study period. This creates maps indicating the relative frequency with which landfast ice occupied any point in the study area, which can be viewed as the probability of finding landfast ice at any point between October and July. The black lines indicate the location of individual SLIEs, which yield contours of frequency. The zones of preferred SLIE occupation seen in Figure 2 are apparent for individual years as regions of strong gradients in frequency and it can be seen that the location and breadth of this zone varies interannually. Figure 3 also shows that, on occasion, stationary sea ice can extend continuously hundreds of kilometers from the coast for at least 20 days. Identification of the SLIE at such distances from the coast can be difficult since discriminating between ice motion and colocation error becomes harder without the land for reference. However, these stable extensions were still often bounded by open water, the significance of which is discussed below.

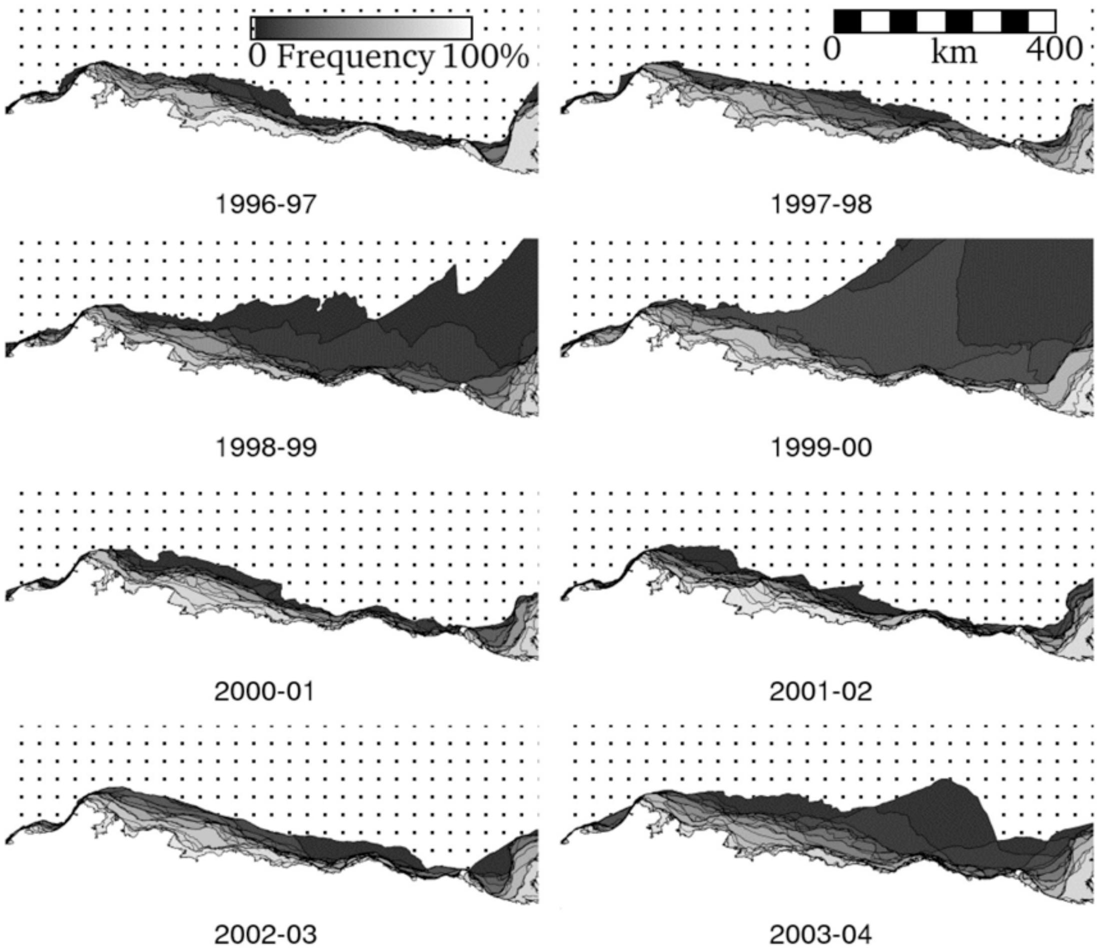

Figure 3. Relative frequency of occurrence of landfast ice between October and July for different years. Dark grey indicates the maximum landfast ice extent. The individual SLIEs resembling frequency contours are shown in black. Landfast ice was never observed in the dotted regions.

DISCUSSION

By examining the spatial distribution of the SLIE along the northern Alaskan coast, we see that there are nodes where the position of the SLIE recurs more often than elsewhere, the locations of which show remarkable agreement between the 20m isobath. However, the reason for this relationship remains unclear. Figure 2 and Figure 3 identify the locations of these nodes, some of which appear constant while others move or are absent in some years. The discrete nature of the nodes suggests that the SLIE is grounded discontinuously along its length, as has been noted previously (Kovacs, 1976; Barry *et al*., 1979), but 20 m is not the maximum keel depth for sea ice. On the contrary, grounded ridges have been observed in deeper water (Stefansson, 1921) and scours on the seabed from keels have been found in water up to 64 m deep (Reimnitz, 1985; Shapiro and Barnes, 1991). Detailed knowledge of the ice thickness distribution of the region during the whole ice season would help address this issue. Ice dynamics probably play a vital role in creating the nodes, not only in deforming the ice so that it is thick enough to become grounded but also in transporting that ice to shallow enough water. The stage of development of the landfast ice when this occurs is also likely to be important since an ungrounded ice cover could prevent deep-keeled ridges getting into shallow water. Tucker *et al.* (1979) describe a series of events by which grounded floes become included in the landfast ice to provide strength and stability. Reimnitz *et al.* (1978) suggest that the promontories in the coast couple with the ice dynamics to create the shoals upon which the ice grounds. In a closer study of the shoals, Reimnitz and Maurer (1978) suggest feedback exists between the creation of shoals and the deformed ice that grounds upon them.

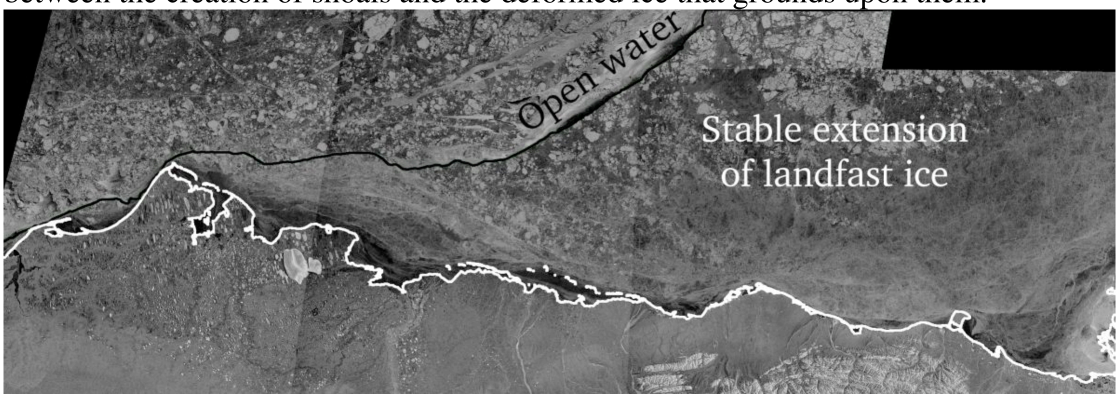

Figure 4 Radarsat mosaic representing the period March 16-18 2000 showing a broad stable extension bounded by an open lead. The SLIE based upon this and the previous and subsequent mosaics is shown in black. This extension persisted without compressive ice stress holding it against the coast for a period of at least 50 days. SAR imagery © Canadian Space Agency (2002)

This study also identified the occurrences of temporary stable extensions when the landfast ice advanced temporarily beyond a position that it later reoccupied when the extension became unstable. Particularly broad extensions occurred during April 1999 and between late February and early April 2000 such that the SLIE was over 250 km from the coast in water over 200 m deep, far beyond the limit of grounded ridges. Closer examination of the April 1999 stable extension shows that on occasions the SLIE extends outside the image and is marked only by shear between moving and stationary ice. It is therefore conceivable that there was an anchoring point somewhere updrift, which allowed the extension to become decoupled from pack ice while some compressive stress held it against the land. By comparison, Figure 4 captures the stable extension that occurred in March 2000 on an occasion when the SLIE was marked by open water. On such occasions, there cannot be any compressive ice stress and so different mechanisms must be holding the extension in place. The oceanographic and ecological consequences of such a broad persistent barrier between the ocean and atmosphere warrant further investigation.

Comparisons were made between our data and those from other sources. The late spring- early summer SLIE positions from Barry *et al.*'s (1978) analysis of the landfast ice between 1973-76 are shown in black on Figure 2. They bear a striking similarity not only in the typical extent of landfast ice but also in the places where they converge. A similar comparison was made with the results of Stringer *et al.*

(1980) for the years 1973,1974 and 1977, which showed much greater variability but still lay within the range occupied by our SLIEs. The indication from this is that the end-of-season landfast sea ice extent has not changed significantly since the 1970's.

We also examined weekly ice charts by the National Ice Center (NIC). A comparison was made for the period February – March 2004, during which time we observed a stable extension. The NIC data differed from ours on a number of occasions. This is partly explained by the longer time period we used in our definition, which led to a more conservative SLIE location. However, on other occasions the NIC charts indicated a lesser landfast ice extent, most likely due to the additional criterion regarding uniformity of color and texture. Whereas we contend that this criterion has little bearing on the stability of landfast ice, we also acknowledge the benefit that hindsight gives us and which is not available for real-time operations.

This then raises questions about the nature of the boundary between the landfast ice and pack ice. Norton and Gaylord (2004) describe a flaw zone of ice that exists in late winter / early spring in the Chukchi Sea, which is influenced by the coast, yet is not stationary. Morris *et al*. (1999) examined the ice motion over 3-day intervals in the East Siberian Sea using SAR. In 21 of their 32 observations between December 24 1993 and March 30 1994, they identified a transitional zone between what they call the stationary-ice zone and the pack ice. Our definition excludes this transitional ice, but understanding the processes that occur within it will be of importance to nearshore development and may help in understanding the mechanisms that lead to stable extensions.

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