ARCTIC
VOL. 65, NO. 2 (JUNE 2012) P. 133–144

# Landfast Sea Ice Conditions in the Canadian Arctic: 1983–2009

RYAN J. GALLEY,[1,2] BRENT G.T. ELSE,[1] STEPHEN E.L. HOWELL,[3] JENNIFER V. LUKOVICH[1] and DAVID G. BARBER[1]

(*Received 13 May 2011; accepted in revised form 2 November 2011*)

ABSTRACT. We used Canadian Ice Service (CIS) digital charts from 1983 to 2009 to create a climatology of landfast sea ice in the Canadian Arctic. The climatology characterized the spatial distribution and variability of landfast ice through an average annual cycle and identified the mean onset date, breakup date, and duration of landfast ice. Trends in date and duration of onset and breakup were calculated over the 26-year period on the basis of CIS regions and sub-regions. In several sub-regions—particularly in the Canadian Arctic Archipelago—we calculated significant trends towards later landfast ice onset or earlier breakup, or both. These later onset and earlier breakup dates translated into significant decreases in landfast ice duration for many areas of the Canadian Arctic. For communities located in the most affected areas, including Tuktoyaktuk, Kugluktuk, Cambridge Bay, Gjoa Haven, Arctic Bay, and Pond Inlet, this shorter landfast ice season is of significant social, cultural, and economic importance. Landfast sea-ice duration in the interior of the Northwest Passage has not undergone any statistically significant decrease over the time series.

Key words: sea ice, landfast, coastal, climatology, variability, trends, Canadian Arctic, onset, breakup, duration, Northwest Passage

RÉSUMÉ. Nous nous sommes appuyés sur les cartes numériques du Service canadien des glaces (SCG) pour les années 1983 à 2009 afin de produire la climatologie de la glace de mer de l'Arctique canadien. La climatologie permet de caractériser la distribution spatiale et la variabilité de la glace de mer au moyen d'un cycle annuel moyen, et de déterminer la date moyenne du commencement, la date de la débâcle et la durée de la glace de mer. Les tendances en matière de dates et de durées relativement au commencement et à la débâcle ont été calculées sur la période de 26 ans en fonction des régions visées par le SCG et des sous-régions. Dans plusieurs sous-régions — plus particulièrement dans l'archipel Arctique canadien — nous avons calculé d'importantes tendances indiquant des dates de commencement plus tardives de la glace de mer ou des dates de débâcle plus hâtives, ou les deux. Ces dates plus hâtives et plus tardives se traduisent par la réduction considérable de la durée de la glace de mer en maints endroits de l'Arctique canadien. Pour les localités situées dans la plupart des régions touchées, dont Tuktoyaktuk, Kugluktuk, Cambridge Bay, Gjoa Haven, Arctic Bay et Pond Inlet, cette saison de glace de mer plus courte revêt une grande importance sur les plans social, culturel et économique. Du point de vue statistique, la durée de la glace de mer à l'intérieur du passage du Nord-Ouest n'a pas connu de réduction importante au cours de cette période.

Mots clés : glace de mer, glace de rive, côtier, climatologie, variabilité, tendances, Arctique canadien, commencement, débâcle, durée, passage du Nord-Ouest

Traduit pour la revue *Arctic* par Nicole Giguère.

Аннотация. Для климатологического анализа припайного льда в Канадской Арктике использованы данные цифровых карт канадской ледовой службы (КЛС) с 1983 по 2009 годы. Данный анализ позволил охарактеризовать пространственное распределение и изменчивость припайного льда на протяжении среднего годового цикла, а также установить средние даты начала замерзания, разлома и продолжительности сезона припайного льда. Средние изменения дат начала замерзания, разлома и продолжительности сезона были рассчитаны для 26-летнего периода для областей и подобластей, используемых КЛС. В нескольких подобластях, в частности, в Канадском Арктическом архипелаге, обнаружена значительная тенденция к более позднему началу замерзания припайного льда и более раннему разлому. Более поздние даты замерзания и более ранние даты разлома привели к значительному сокращению сезона припайного льда для многих регионов Канадской Арктики. Для населенных пунктов, расположенных в наиболее подверженных этому изменению областях (в том числе Тектоякчек, Куглуктук, Кеймбридж Бей, Йоа-Хейвен, Арктик-Бей и Понд-Инлет) более короткий сезон припайного льда может иметь существенное культурное и экономическое значение. Проведенный анализ не показал статистически значимого снижения

[1] Centre for Earth Observation Science, University of Manitoba, Winnipeg, Manitoba R3T 2N2, Canada
[2] Corresponding author: galley@cc.umanitoba.ca
[3] Climate Processes Section, Climate Research Division, Science and Technology Branch, Environment Canada, Government of Canada, 4905 Dufferin Street, Toronto, Ontario M3H 5T4, Canada

продолжительности сезона припайного льда в бассейне Северо-Западного морского пути за рассматриваемый период времени.

Ключевые слова: морской лед; припайный лед; прибрежная зона; климатология; изменчивость; тренды; Канадская Арктика; начало замерзания; начало разлома; продолжительность сезона; Северо-Западный морской путь

## INTRODUCTION

Landfast sea ice is defined as motionless sea ice that is attached either to the shore, or to ice walls or fronts, or between shoals or grounded icebergs. It may be formed in situ or by the amalgamation of floating ice of any age freezing to the shore (CIS, 2002). Landfast sea ice is a predominantly seasonal feature of the Arctic, with extents ranging from 5–50 km off the coast of Alaska to several hundred kilometers off the coast of Siberia (e.g., Divine et al., 2004). Water depths associated with the landfast ice edge are on the order of 25 m near the Siberian coast, 8–30 m in the Beaufort Sea, and 100 m off the eastern coast of Baffin Island (Mahoney et al., 2007).

The physical interaction between landfast sea ice, mobile pack ice, and the underlying ocean continues to be a topic of research interest. Areas of open water at the interface between landfast and mobile sea ice increase the potential for solar heating, and they make the ice edge vulnerable to wind waves and swell (Fox and Squire, 1990; Squire et al., 1995). The role of landfast ice in either preventing or aiding upwelling circulation has been a topic of study for decades (e.g., Clarke, 1978; Buckley et al., 1979; Carmack and Kulikov, 1998; Carmack and Chapman, 2003). When adjacent to open water, a landfast ice edge can act as the boundary necessary to give rise to divergence in the wind-driven surface current, producing upwelling (Clarke et al., 1978; Buckley et al., 1979). However, a fast-ice surface without adjacent open water acts as a barrier to momentum exchange between the atmosphere and ocean, preventing upwelling that might occur if the ice were mobile (Pickart et al., 2009). The interplay between the landfast ice edge, pack ice edge, bathymetry, and winds favourable to upwelling governs the transport of nutrients to the surface and thus biological productivity. Interesting physical-biological interactions occur as a result of these linkages; for example, ice-edge phytoplankton blooms often occur in spring as a result of upwelled nutrients (Mundy et al., 2009).

Landfast sea ice is important from an economic perspective because it can be detrimental to ship navigation. Depending on its thermodynamic state, landfast sea ice can be much more difficult to navigate through in comparison to even very high concentrations of mobile pack ice. However, offshore oil and gas exploration may be easier in landfast sea-ice zones than in areas of mobile pack ice. The presence of landfast ice also has important implications for northern communities in the context of coastal erosion, transportation and winter road development, and subsistence and commercial activities. A concerted effort has been initiated to provide a continuous measure of ice conditions in northern communities throughout the Canadian Arctic that links traditional knowledge with scientific knowledge (Laidler et al., 2009).

Regional variations exist in landfast ice formation and decay throughout the Arctic. Investigation of the seaward landfast ice edge from 1996 to 2004 shows that landfast ice extent along the Alaskan coast is governed by bathymetry as opposed to changes in climate, in contrast to the Laptev, Chukchi, and East Siberian Seas, which are governed by dynamic and thermodynamic forcing mechanisms (Polyakov et al., 2003; Mahoney et al., 2007). Although landfast ice forms gradually in fall, fast-ice cover decays comparatively rapidly in spring, as dynamic atmospheric and oceanic forcing mechanisms exert their influence on an ice cover weakened by increasing temperatures and downwelling radiation (Persson et al., 2002). Decay can be further expedited by offshore winds or wave action (Squire, 1993; Squire et al., 1995). River discharge can also influence landfast ice extent and breakup (Dmitrenko et al., 1999). As thawing rivers flood sea ice and deposit sediments, they also transport heat from the terrestrial to the marine environment (Dean et al., 1994; O'Brien et al., 2006).

An area where landfast sea ice is of particular importance is the Canadian Arctic Archipelago (CAA), which constitutes 15–20% (roughly 1.9 million km$^2$) of the area of the Arctic Ocean and its peripheral seas (Melling, 2002). A unique characteristic of the CAA is that the majority of the sea ice in the region remains landfast for six to eight months of the year (Melling, 2002). This landfast sea ice restricts ice drift in the CAA for more than half the year (Marko, 1977). If the sea ice is not landfast during the summer, it travels very slowly through the numerous shallow and narrow channels of the CAA, where internal ice pressure due to horizontal restrictions mostly stops ice drift (Melling, 2002). Landfast sea-ice properties in the CAA have long been considered relevant in discussions of climate change at high latitudes (e.g., Brown and Cote, 1992; Flato and Brown, 1996).

It is well known that mobile sea ice in the Northern Hemisphere has experienced significant reductions in both its thickness (Rothrock et al., 1999; Rothrock and Zhang, 2005) and its extent (Comiso, 2006; Stroeve et al., 2007; Perovich et al., 2008; Perovich and Richter-Menge, 2009). Comparatively little is known about landfast sea-ice climatology, especially in the CAA. Seasonal landfast ice in the CAA behaves thermodynamically and chronologically much differently from ice in the Beaufort Sea, in part because of its proximity to land (Flato and Brown, 1996). Some trends in landfast sea ice have been studied; landfast ice now forms a week later in the southwestern Beaufort Sea than it did in the 1970s because fast ice formation is sensitive to the position of the perennial ice pack, which has retreated in recent years (Mahoney et al., 2007). A shortening in the landfast season is consistent with modeling studies. For example, Dumas et al. (2005) showed a three-week reduction in landfast ice duration and a 24 cm reduction in mean maximum ice thickness when air temperature was increased by 4˚C and the snow accumulation rate was increased by 20%.

The CAA creates a much different icescape than the central Arctic Ocean because of its distinctive topography, bathymetry, and climatological conditions, and landfast sea ice is not currently incorporated into global climate models. Despite the importance of landfast ice to the CAA, no studies describing its climatology or trends in timing and distribution are currently available. The goals of this work are to determine (1) the climatology of landfast sea ice in the Canadian Arctic and (2) spatiotemporal changes in landfast ice over the last several decades in the Canadian Arctic. In this study we examine regional variations in landfast ice formation and decay. We also examine statistically significant trends in landfast ice breakup and onset dates and duration to improve our understanding of changing landfast ice conditions and their effect on northern coastal communities over the last several decades.

## DATA AND METHODS

The sea-ice data used in this study were obtained from the Canadian Ice Service (CIS) Digital Archive (CISDA: http://ec.gc.ca/glaces-ice/). The CISDA is a compilation of Canadian Ice Service regional weekly ice charts that integrate all available real-time information about sea ice gathered from various satellite sensors, aerial reconnaissance, ship reports, operational model results, and the expertise of experienced ice forecasters. These digital ice charts are topologically complete polygon ArcInfo Geographic Information System coverages.

The CISDA delineates polygons of similar ice conditions using the egg code: each polygon is given a total sea-ice concentration composed of up to three partial sea-ice concentrations by type (/10ths). Digitally available CIS charts in the years 1983 to 2009 (inclusive) for both the eastern and western Arctic CIS regions were converted to a 2 × 2 km grid on the native CIS Lambert conformal conic projection. Grid cells with total sea-ice concentration of 10/10ths were considered to be landfast. This classification is consistent with the method of Melling (2002), which takes into account that the CISDA uses the 10/10ths concentration classification only for fast ice, employing a 9.7/10ths classification for even the highest concentrations of mobile sea ice. This approach also allowed us to avoid using the "fast ice" designation in the floe size portion of the egg code, which has not always been consistent between the eastern and western Arctic (Tivy et al., 2011) and is incomplete in the time series. Wohlleben et al. (2010) compared our means of determining landfast sea-ice duration with published estimates from RADARSAT-1 SAR data in Nares Strait (Kwok et al., 2010) and found the two data sets to be very similar for the years 1997–2009. As a final quality control, we checked each grid to ensure that mobile sea ice (not connected to the coast) was excluded from the analyses.

Source information used in preparing the ice charts has changed over time because of advances in sensor technology and changes in regional shipping routes (Tivy et al., 2011). Despite this, the CISDA has been found sufficiently accurate for time series analyses (e.g., Kinnard et al., 2006; Galley et al., 2008; Howell et al., 2009; Tivy et al., 2011) and is in fact more accurate than passive microwave ice concentration retrievals during the melt season (Agnew and Howell, 2003). Spatiotemporal quality indices for the CISDA can be found in Tivy et al. (2011). These indices take into account the availability and quality of ship observations, airborne observations, airborne synthetic aperture radar (SAR) or side-looking airborne radar (SLAR), or both, and satellite data. We acknowledge the potential impact of technological change on the reported sea-ice conditions, but satellite data have been the primary source since 1979, before the starting point of our time series. We chose to use data from 1983 onward because in 1983 the CIS switched to the egg code from the older ratio code to allow for more accurate recording of sea-ice stage of development, marking the beginning of the fourth of six time periods identified as being significant in the data quality of the CISDA (Tivy et al., 2011). For the period and regions we studied, the quality indices are of average confidence between 1983 and 1990 and very high confidence thereafter.

Using the CISDA, we performed the following calculations:

- The *percent of the year* during which each grid cell was landfast was calculated by dividing the number of weeks that a grid cell was landfast in a sea-ice year (01 September to 31 August) by the total number of charts in that sea-ice annual cycle. The mean for the period (1983–84 to 2008–09) was then calculated for each grid cell. The standard deviation from the mean was also calculated.

- For each grid cell, the *percent annual occurrence* of landfast sea ice through the period was calculated by finding the number of years in the period studied when landfast sea ice occurred in that cell.

- The *average annual evolution* of landfast sea-ice presence was calculated by determining the percent of years in which landfast ice occurred in a grid cell for each year-week between 1983–84 and 2008–09.

- For each sea-ice year, the *landfast onset date* was considered to be the first date between consecutive Septembers on which landfast sea ice was present, and the *landfast breakup date*, the last date between 01 September and 31 August in consecutive years when landfast sea ice was present. The annual (n = 25) landfast sea-ice

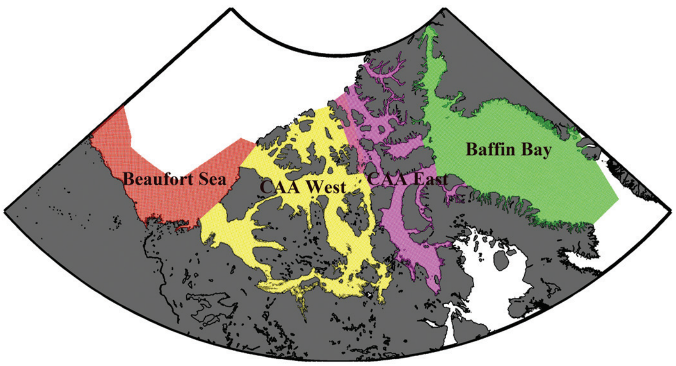


FIG. 1. Study area, with CIS ice regions delineated by colour: the Beaufort Sea (red), CAA-West (yellow), CAA-East (purple), and Baffin Bay (green).

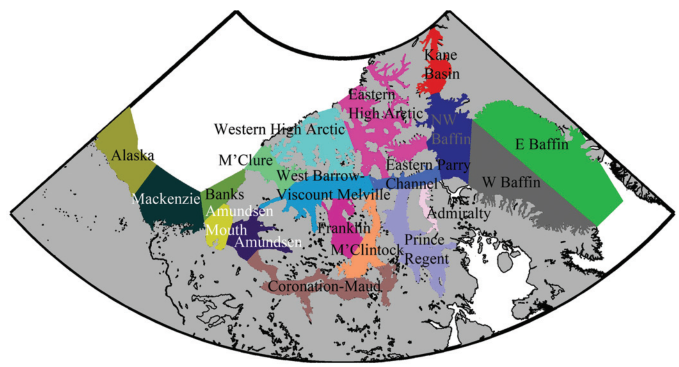


FIG. 2. Study area, with CIS sub-regions delineated.

onset and breakup dates were used to calculate the mean onset and mean breakup date for each grid cell over the time series. The standard deviation was also calculated to determine the variability from the mean of onset and breakup at each grid cell through the time series. Both onset and breakup of landfast sea-ice were calculated using the same time step used in the average annual evolution of landfast sea-ice calculations; therefore, the standard deviation for the onset and breakup dates was calculated in year-weeks.

- *Landfast sea-ice duration* for each grid cell in each annual cycle was calculated in weeks by calculating the number of weeks between onset and breakup (inclusive).

Using the CIS ice regime regions as a template, we calculated regional (Fig. 1) and sub-regional (Fig. 2) trends in mean onset, breakup, and duration of landfast sea ice for all the grid cells in each region and sub-region, using the method of least squares fit regression. The significance of each trend was tested using a standard F-test. The onset, breakup and duration data were tested for normality, and autocorrelation was found to be sufficiently low to allow for parametric analysis. Any trend with an associated $p$-value equal to or less than 0.05 was considered statistically significant. The percentage of each region that was landfast on the mean onset and breakup dates each year was also calculated.

## RESULTS: FAST ICE CLIMATOLOGY

### *Average Spatial Distribution of Landfast Ice*

Fast ice was spatially and interannually variable in the Canadian Arctic between 1983 and 2009. Much of the ocean surface in the CAA was landfast for some portion of each sea-ice year (Fig. 3a). Areas near the edges of the CAA, including the periphery of the Western High Arctic, Amundsen Gulf, M'Clure Strait, Lancaster Sound, Prince Regent Inlet and the Gulf of Boothia, were landfast for the shortest amount of time each year (Fig. 3a in blue) and also had comparatively low percent-occurrence values over the record (Fig. 3b). These peripheral areas did not experience landfast sea ice every year and exhibited greater variability between years in the duration of that ice (Fig. 3c).

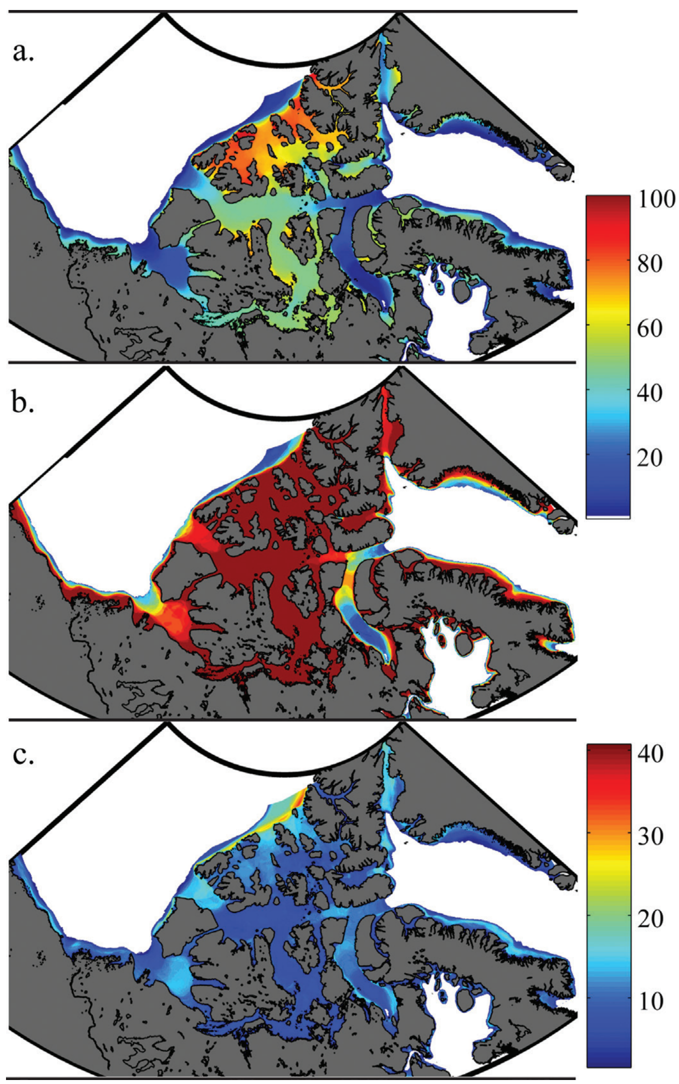


FIG. 3. (a) Mean percent of the year (n = 26 years) during which each grid cell was landfast, (b) the percent occurrence of landfast sea ice in each grid cell between 1983 and 2009, and (c) the standard deviation from the mean percent of the year for which each grid cell was landfast.

In the southern interior of the CAA (south of ~75˚ N), the sea ice was landfast for about half of each sea-ice year on average in the Franklin, M'Clintock Channel, and West Barrow-Viscount Melville sub-regions (Fig. 3a). These sub-regions experienced landfast sea ice in each year of the time series (Fig. 3b), and variability in the portion of each sea-ice year when these areas were landfast was comparatively low (Fig. 3c). On average, the Western and Eastern High Arctic sub-regions were landfast for most of the year (Fig. 3a), and there was marginally greater variability nearest the northwest coast of the CAA (Fig. 3c). In Kane Basin and Smith Sound, the sea ice was landfast for a comparatively short time in each sea-ice year (Fig. 3a), though this area was landfast in almost all the years studied, if only briefly (Fig. 3b). This area also experienced greater interannual variability in the duration of landfast ice than the interior of the CAA (Fig. 3c).

### *Average Annual Evolution of Landfast Sea Ice*

In Figure 4, we mapped the mean spatial distribution of landfast sea ice for each year-week in the CISDA to represent the annual evolution of landfast ice in the Canadian Arctic. Multiyear landfast ice persisted through the summer (and was thus present in early September) only in the High Arctic and only in 20–40% of years (Fig. 4). Although they did not always start the year landfast, most areas in the High Arctic were usually landfast by mid-November. After the High Arctic areas, the second areas to begin to form landfast ice were the southern channels of the CAA, including the Coronation-Maud, Franklin, M'Clintock, and coastal Amundsen sub-regions (Fig. 4). These areas can become landfast as early as the first week in November and were landfast in most years by early January. Landfast ice formed slightly later in the interior of the CAA (M'Clure, West Barrow-Viscount Melville) and along the peripheries (Kane Basin and West Baffin), with formation by mid-November in years of early landfast ice onset and by the end of January in most years. The sub-regions with the latest landfast ice onset were Amundsen Mouth, Eastern Parry Channel, and Prince Regent, with onset occurring at some point in January. In more than 50% of years, these sub-regions never became landfast.

June 18 is the first year-week when the likelihood of landfast ice began to decrease, marking the start of the summer breakup season. The areas that were latest to form landfast ice (i.e., the peripheries of the CAA) were the earliest to break up. The southern areas of Coronation-Maud were the next to break up, becoming free of landfast ice by mid-July in most years. They were followed by the M'Clure, West Barrow-Viscount Melville, Franklin, M'Clintock, and Kane Basin sub-regions, which were free of landfast ice by early August in most years. The last area to lose landfast ice was the High Arctic, where, as mentioned previously, the ice sometimes persists through the summer.

### *Average Fast-Ice Onset and Breakup Dates and Their Variability*

Landfast sea ice did not always occur each year in every grid cell (Figs. 3b, 4). The average dates of landfast onset and breakup are explored here, along with their variability. Landfast sea-ice onset is mapped in Figure 5a, which summarizes the annual evolution information in Figure 4 and sets a frame of reference for the onset variability information in Figure 5b.

The Coronation-Maud sub-region showed the earliest and least variable landfast sea-ice onset in the time series, followed by the Eastern and Western High Arctic sub-regions (Fig. 5b). Landfast onset was slightly more variable in the central CAA, where landfast ice usually occurred next in the annual sea-ice cycle (Fig. 5b); the Eastern Parry Channel and Prince Regent sub-regions (Fig. 5b) experienced the lowest occurrence of landfast sea ice (Fig. 3b) and the latest onset (Fig. 5a) in the period. Amundsen, Amundsen Mouth, and M'Clure on the western periphery of the CAA had greater variability than the central CAA and experienced onset comparatively late in the annual cycle (Fig. 5a). This was especially true where the percent occurrence of landfast sea ice in M'Clure and Amundsen Mouth dropped rapidly toward the western edges (Fig. 3b). The greatest onset variability occurred along the west coast of the Canadian Arctic Archipelago and along the north continental coast of Canada and Alaska west of Cape Bathurst, where the landfast sea ice grows outward from the coast and into the Beaufort Sea unconstrained (Fig. 5b).

Breakup ends the annual evolution of landfast sea ice in the Canadian Arctic (Fig. 6a). There was very little variability in landfast breakup date in much of the interior of the CAA, including Coronation-Maud, Franklin, M'Clintock, West Barrow-Viscount Melville, and the Western and Eastern High Arctic sub-regions (Fig. 6b), which were landfast in almost all the years studied (Fig. 3a). When landfast ice occurred in the north end of the Prince Regent sub-region, variability in its breakup date was low (Fig. 6b). Variability in the breakup date was high in Kane Basin, and in Amundsen, Amundsen Mouth, M'Clure, the south half of the Prince Regent sub-region, and Eastern Parry Channel (Fig. 6b). These sub-regions are highly variable in all of the metrics we examined, including occurrence of landfast ice (Fig. 3b) and onset date (Fig. 5b). There were some small areas of very high variability in the mean breakup date along the northwest coast of the CAA (Fig. 6b), but these were likely due to the limited number of times landfast sea ice actually occurred and broke up there during the study period (Fig. 3b).

## RESULTS: TRENDS IN LANDFAST SEA ICE

### *Trends in Landfast Onset and Breakup Dates*

For each year, we calculated the mean onset and breakup dates of all grid cells within the CIS regions (Fig. 1) and

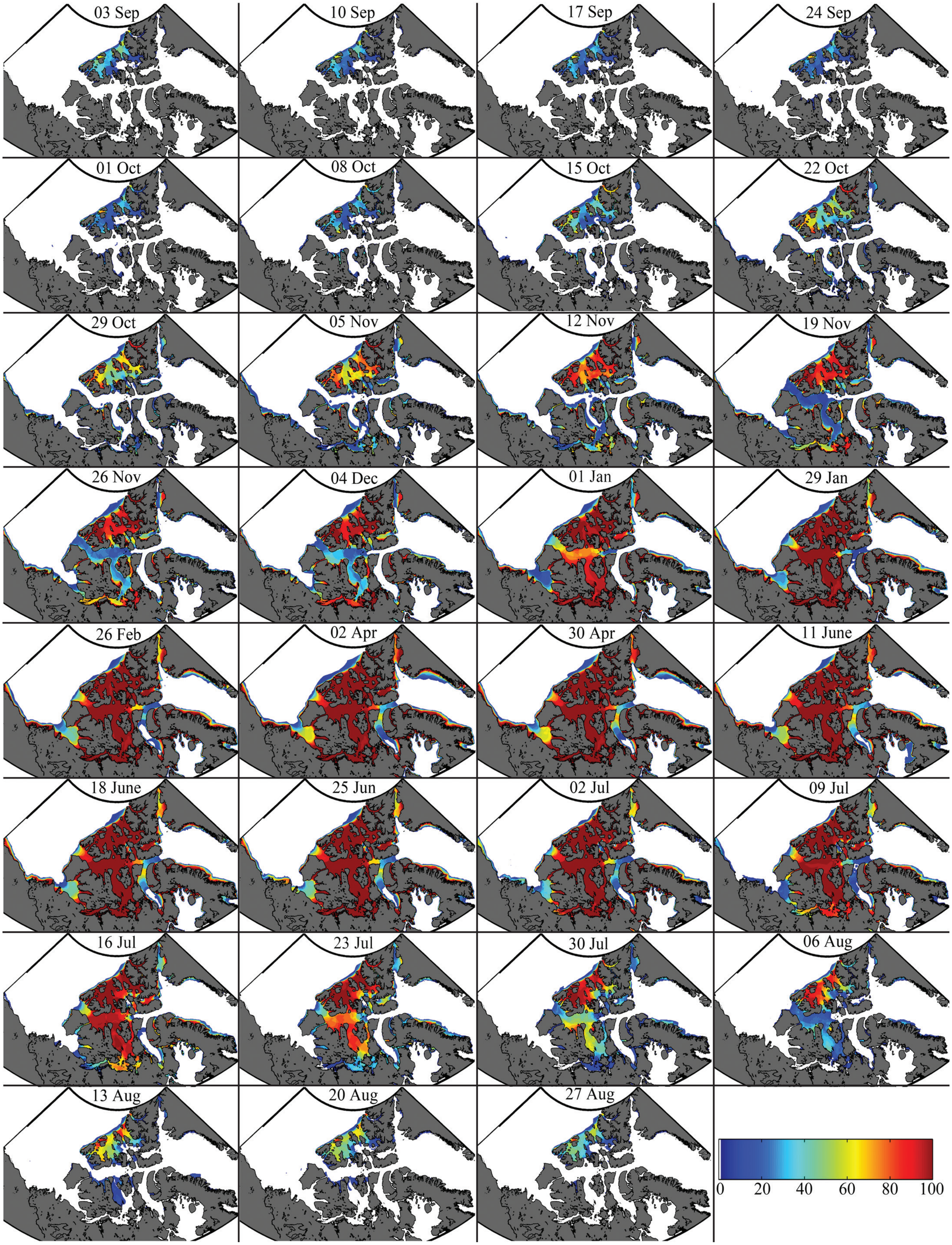


FIG. 4. The annual evolution of landfast sea-ice presence: weekly mean spatial distribution of landfast ice occurrence in the Canadian Arctic between 1983 and 2009.

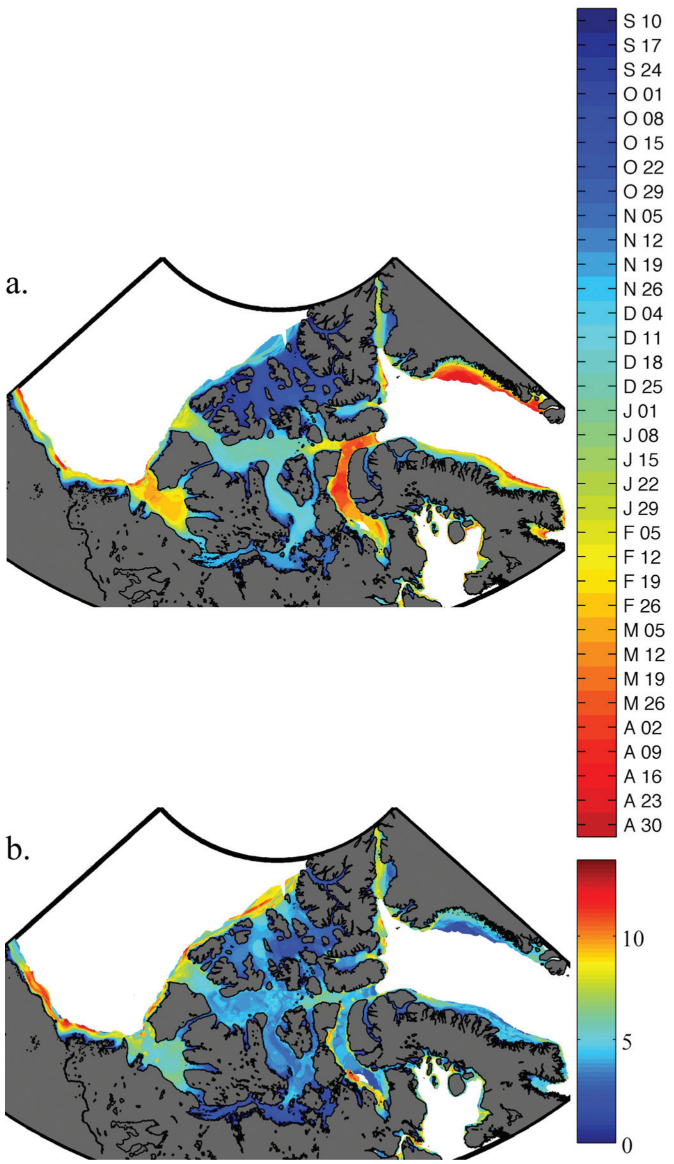


FIG. 5. (a) Mean date of landfast sea-ice onset in the Canadian Arctic for the years 1983–2009 (given as month day: e.g., S 10 = September 10) and (b) standard deviation in weeks of landfast sea-ice onset in the Canadian Arctic.

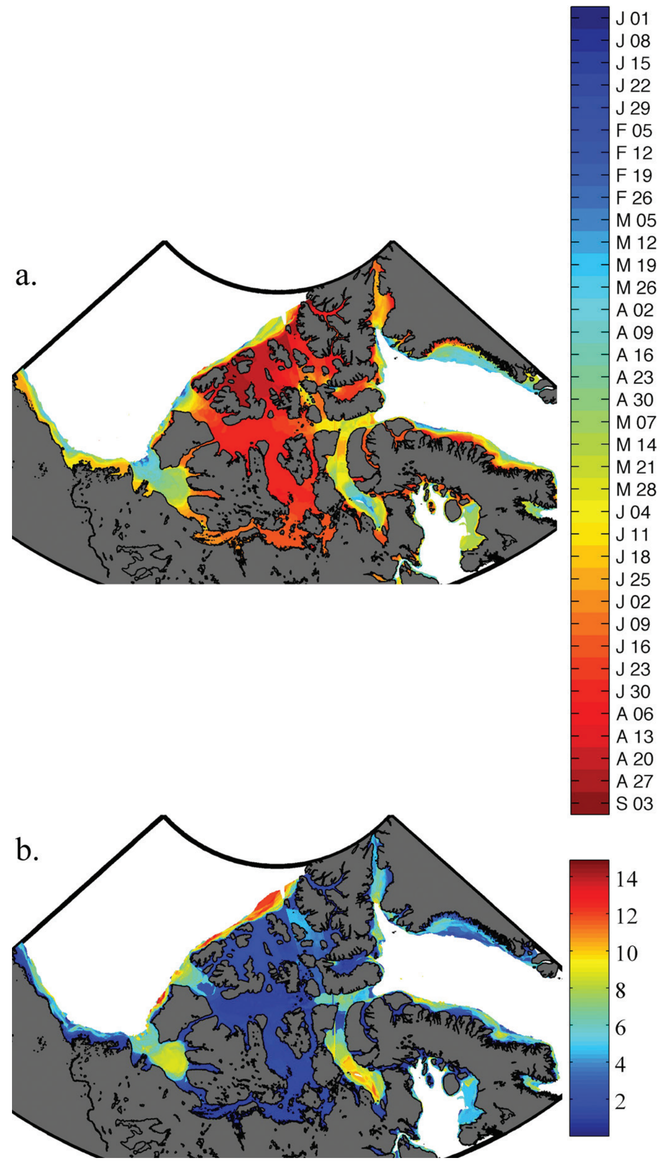


FIG. 6. (a) Mean date of landfast sea-ice breakup in the Canadian Arctic for the years 1983–2009 (given as month day: e.g., S 10 = September 10) and (b) standard deviation in weeks of the date of landfast sea-ice breakup in the Canadian Arctic.

sub-regions (Fig. 2) and regressed those means against time to examine trends over the study period. The larger regional landfast sea-ice onset and breakup date trends and their associated *p*-values are shown in Table 1. The CAA-West and CAA-East regions exhibited trends towards later onset date (0.64 and 1.07 weeks•decade$^{-1}$) and trends towards earlier breakup date (-0.57 and -0.89 weeks•decade$^{-1}$ respectively). The trends in both onset and breakup dates of landfast ice are statistically significant in CAA-East (Table 1). The time series for this region is shown in Figure 7 (top two panels). In both CAA-East (Fig. 7: bottom) and CAA-West (not shown), landfast ice is the dominant surface type (accounting for ~80–100% of the regions) at both onset and breakup.

In contrast, in the regions at the exterior of the CAA, the Beaufort Sea (Fig. 8: bottom) and Baffin Bay (not shown), landfast sea-ice cover at onset and breakup is only ~20%. The Beaufort Sea and Baffin Bay regions also exhibited trends towards later landfast onset date (2.78 and 0.64 weeks•decade$^{-1}$) and earlier breakup (-0.65 and -0.62 weeks•decade$^{-1}$) (Fig. 8, Table 1).

The Beaufort Sea region is composed of the Alaska, Mackenzie, and Banks sub-regions (Fig. 2). The Alaska (2.87 weeks•decade$^{-1}$) and Mackenzie (2.80 weeks•decade$^{-1}$) sub-regions drove much of the trend toward later onset of landfast ice in the Beaufort Sea (Table 2), and these results are in general agreement with those of Mahoney et al. (2007). The Banks sub-region showed a trend toward later onset of landfast sea ice, but this trend was not statistically significant (Table 2). The trends toward earlier breakup of landfast sea ice in the same sub-regions were not statistically significant (for $p \leq 0.05$) (Table 2).

TABLE 1. Regional trends (weeks/decade) in onset and breakup dates for the CIS ice regions shown in Figure 1. Values in bold are statistically significant at $p \leq 0.05$.

| Region | Onset trend | Onset *p*-value | Breakup trend | Breakup *p*-value |
|---|---|---|---|---|
| Beaufort Sea | **2.78** | **0.0004** | **-0.65** | **0.05** |
| CAA - West | 0.64 | 0.13 | -0.57 | 0.07 |
| CAA - East | **1.07** | **0.03** | **-0.89** | **0.005** |
| Baffin Bay | 0.64 | 0.11 | -0.62 | 0.08 |

In the CAA-West region, the trends in both average onset and average breakup of landfast sea ice were not statistically significant, but sub-regional analysis revealed statistically significant trends in some sub-regions. Statistically significant trends towards later landfast sea-ice formation appeared at Coronation-Maud in the south (at 0.85 weeks•decade$^{-1}$) and the Western High Arctic sub-region in the north (1.24 weeks•decade$^{-1}$) (Table 2). The Western High Arctic sub-region also showed a trend toward earlier landfast sea-ice breakup since 1983 (-0.87 weeks•decade$^{-1}$) (Table 2).

Within the CAA-East region, significant sub-regional trends toward later onset (1.20 weeks•decade$^{-1}$) and earlier breakup (-0.95 weeks•decade$^{-1}$) occurred in the Eastern High Arctic sub-region. Similar trends occurred in the Eastern Parry Channel sub-region, but they were not statistically significant (Table 2). Admiralty Inlet experienced a significant trend toward later landfast onset (1.4 weeks•decade$^{-1}$) over the period (Table 2), but no significant trend towards earlier breakup.

Neither the Baffin Bay region (Fig. 1) nor any of its sub-regions (Fig. 2) experienced statistically significant trends in their onset dates (Tables 1, 2). Trends in breakup date were also not significant in these sub-regions except in Western Baffin Bay, which experienced a declining trend of -0.9 weeks•decade$^{-1}$ (Table 2). The lack of significant trends in most of the Baffin Bay sub-regions was probably due to the high inter- and intra-annual variability associated with the chronology and location of landfast ice occurrence, as described in previous sections (note that the *p*-value for the trend in breakup date in Kane Basin, though not significant, is quite low).

### *Trends in Landfast Ice Duration*

Trends in the duration of the landfast sea-ice season were calculated for each grid cell in each year as the difference between breakup date and onset date (Fig. 9). The real value of zero was assigned to any grid cells that did not have an onset date. Trends in landfast sea-ice duration were mapped for each grid cell (Fig. 9) to show the change in weeks•decade$^{-1}$ through the study period. In the Beaufort Sea, significant negative trends in landfast sea-ice duration occurred along the coasts of the Alaska, Mackenzie, Banks, Amundsen Mouth, and Amundsen sub-regions (Fig. 9) in areas where landfast sea ice occurred each year (Fig. 3b). In Canada's Queen Elizabeth Islands, much of the Western and Eastern High Arctic sub-regions experienced significant

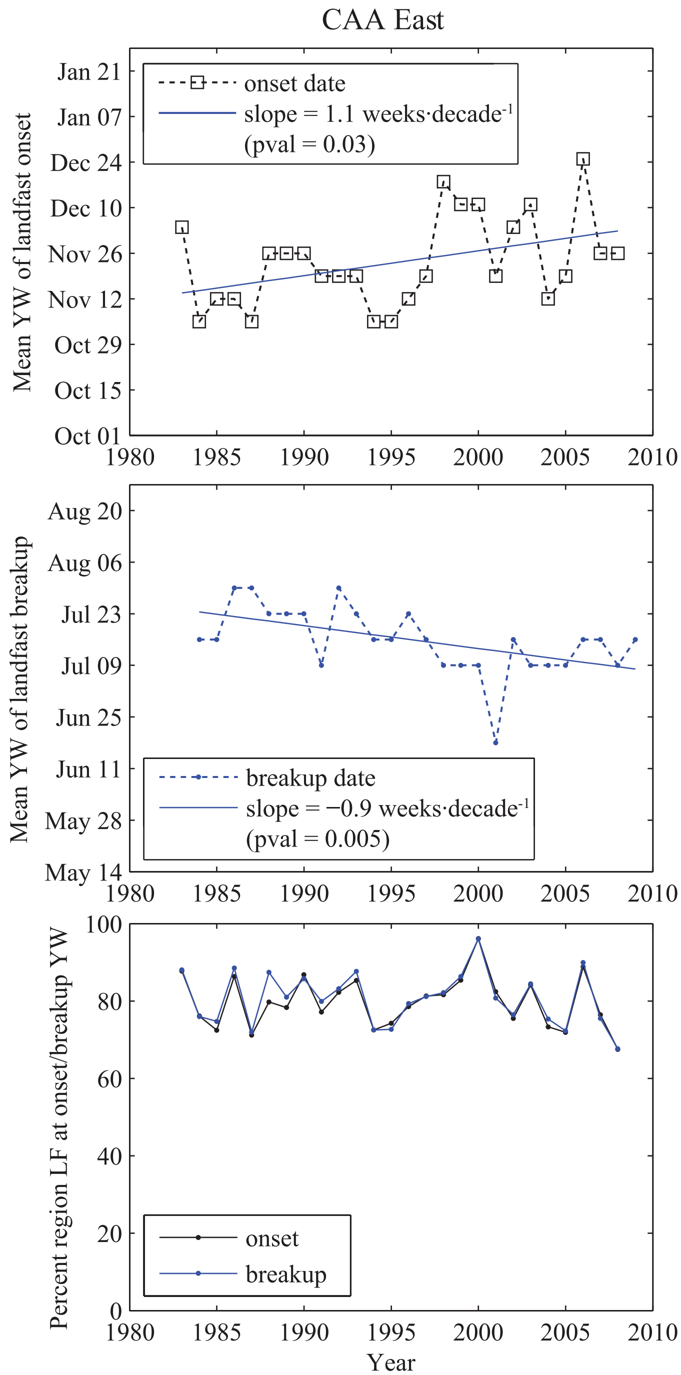


FIG. 7. CAA-East Region: Trends in dates of onset (top) and breakup (middle) of landfast ice and the percent of the region that is landfast on those dates (bottom).

TABLE 2. Sub-regional trends (weeks/decade) in onset and breakup dates for the CIS sub-regions shown in Figure 2. Values in bold are statistically significant at $p \leq 0.05$.

| Region | Sub-region | Onset trend | Onset *p*-value | Breakup trend | Breakup *p*-value |
|---|---|---|---|---|---|
| Baffin Bay | E Baffin Bay | 0.44 | 0.47 | -0.15 | 0.71 |
| | NW Baffin Bay | 0.52 | 0.39 | -0.68 | 0.09 |
| | W Baffin Bay | 0.62 | 0.12 | **-0.92** | **0.05** |
| | Kane Basin | 1.15 | 0.13 | -1.72 | 0.06 |
| Beaufort Sea | Alaska | **2.88** | **0.005** | -0.62 | 0.1 |
| | Banks | 0.97 | 0.44 | -1.17 | 0.14 |
| | Mackenzie | **2.80** | **0.0007** | -0.34 | 0.16 |
| CAA-West | Amundsen | 0.56 | 0.59 | -0.78 | 0.56 |
| | Amundsen Mouth | 0.096 | 0.93 | -0.22 | 0.79 |
| | Coronation-Maud | **0.85** | **0.03** | -0.13 | 0.64 |
| | Franklin | 0.44 | 0.43 | -0.50 | 0.14 |
| | M'Clintock Channel | 0.48 | 0.36 | -0.56 | 0.09 |
| | M'Clure Strait | 1.25 | 0.17 | -1.16 | 0.14 |
| | West Barrow - V. Melville | -0.17 | 0.77 | **-0.63** | **0.02** |
| | Western High Arctic | **1.24** | **0.03** | **-0.87** | **0.02** |
| CAA-East | Eastern High Arctic | **1.20** | **0.02** | **-0.95** | **0.002** |
| | Admiralty Inlet | **1.41** | **0.003** | -0.53 | 0.07 |
| | Eastern Parry Channel | 1.58 | 0.07 | -1.55 | 0.08 |
| | Prince Regent | 0.88 | 0.26 | -0.91 | 0.21 |

reductions in landfast sea-ice duration (Fig. 9), on the order of about 2–5 weeks•decade$^{-1}$. Significant negative trends in landfast sea-ice duration also occurred in the eastern half of M'Clure Strait where landfast sea ice occurred each year (Fig. 3b), along the north and east coasts of Victoria Island, in much of the Coronation-Maud sub-region, and along the coasts of Prince of Wales and Somerset Islands (Fig. 9).

In the eastern Arctic, significant negative trends in landfast sea-ice duration occurred in the south end of the Prince Regent sub-region, in Admiralty Inlet, and between Bylot Island and Baffin Island (Fig. 9) where fast ice occurred each year (Fig. 3b). Kane Basin and the coastline areas of Northwest, West, and East Baffin Bay also all experienced significant negative trends in landfast sea-ice duration (Fig. 9) where landfast sea ice occurred each year (Fig. 3b). Significant negative trends in duration of annual landfast sea ice were also observed in areas that demonstrated substantial variability in onset and breakup through the time series (Figs. 5b, 6b), including the eastern half of the M'Clure sub-region, the north continental coast of the Mackenzie and Alaska sub-regions, Kane Basin, and the coasts of the West Baffin, Northwest Baffin, and East Baffin sub-regions.

## DISCUSSION

The human importance of landfast sea ice in the Canadian Arctic lies in its utility or detriment to stakeholders. Landfast sea ice is important to Inuit communities as a platform from which to hunt, fish, and travel (e.g., Berkes and Jolly, 2001; Ford et al., 2008; Laidler et al., 2009). It may be a barrier to economic development, or enable it. Observed trends (Table 2) and variability (Fig. 3c) in the landfast sea-ice regime of the Mackenzie sub-region will affect the inhabitants of Tuktoyaktuk, and changes observed in the landfast sea-ice regimes of the Coronation-Maud sub-region will affect those who make their homes in Kugluktuk, Cambridge Bay, and Gjoa Haven. In these sub-regions, the observed trends in landfast ice duration (Fig. 9) connote a landfast ice season that is now 2–10 weeks shorter on average. The effects of reduced landfast sea-ice duration in these areas, whether manifested by delayed onset, earlier breakup, or both, will have important impacts on their inhabitants (e.g., Ford et al., 2009). Landfast sea ice offshore of Tuktoyaktuk protects the town's coastline from erosion caused by wave action, and landfast sea ice forms the winter road between Tuktoyaktuk and communities of the Mackenzie delta. In recent years, companies have become interested in offshore oil and gas exploration both within and outside of the landfast sea-ice zone in the area. Cambridge Bay stands potentially to gain economically from reduced duration of landfast sea ice in the future, as it was recently named the site for Canada's new High Arctic research station. Observed reductions in landfast sea-ice duration in the Admiralty Inlet sub-region (Fig. 9) could potentially vitalize the community of Arctic Bay as the Canadian Forces turn the former Nanisivik port into a deep-water facility that will berth and refuel Canadian Forces ships patrolling the entrance to the Northwest Passage.

While the Northwest Passage is a less elusive shipping route than it was when it was first sailed by Roald Amundsen in 1903–06, our results show that the landfast sea ice in many of the navigable channels of the CAA is as pervasive now as it was 26 years ago. We observed no decrease in the landfast sea-ice duration in many of the sub-regions that make up the Northwest Passage, including Amundsen, Franklin, M'Clintock, West Barrow-Viscount Melville, and Prince Regent (Table 2). This result has implications not only for shipping, but also for the cruise tourism industry, which may be experiencing a false sense of optimism regarding new opportunities in the Northwest Passage (Stewart et al., 2007).

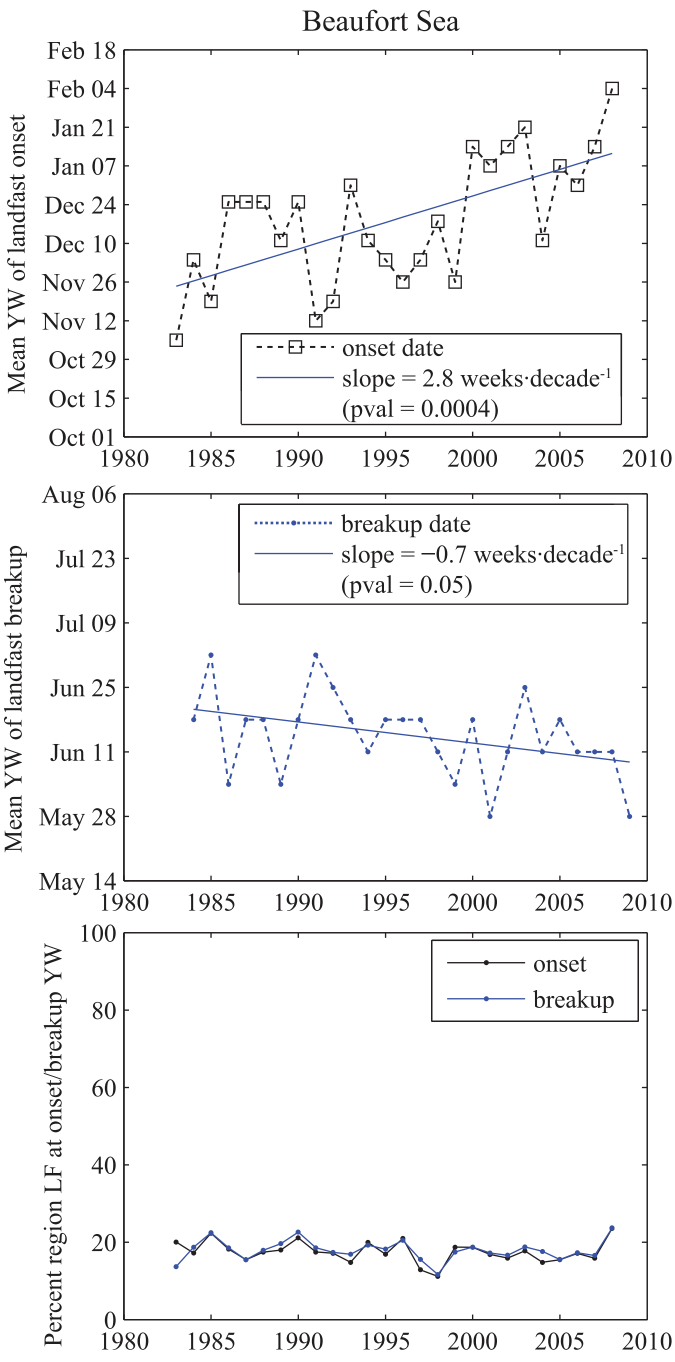


FIG. 8. Beaufort Sea Region: Trends in dates of onset (top) and breakup (middle) of landfast ice and the percent of the region that is landfast on those dates (bottom).

Climatologically, landfast sea ice is especially important in the Arctic physical system because it all but restricts the flow of energy from the atmosphere to the ocean in the spring. Open water areas are important to the timing of seasonal sea-ice melt because of the sea ice – albedo feedback mechanism (e.g., Perovich et al., 2008): even very small amounts of lead area in a sea-ice cover have been shown to dominate the regional surface energy balance (Maykut, 1978). Since decreases in landfast ice duration imply increases in open water, observed trends towards a shorter landfast season (Fig. 9) must be causing increased solar energy absorption in some areas of the CAA.

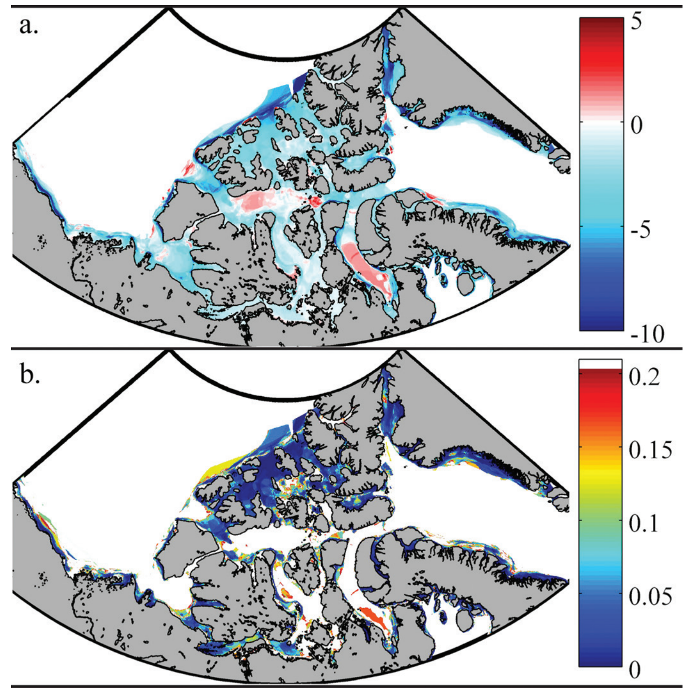


FIG. 9. (a) Trend in duration of landfast sea ice (weeks/decade) in the Canadian Arctic between 1983 and 2009 and (b) associated *p*-values for the linear regressions.

Finally, landfast ice is an important biological habitat, not only for polar bears (Ferguson et al., 2000) and seals (Smith and Hammill, 1981), but also for the lower trophic levels of the ecosystem. Although for most of the year light transmission is limited through landfast ice, sub-ice primary production has evolved to take advantage of a range of irradiance conditions dictated by the seasonality, thickness, and snow cover associated with landfast sea ice (Welch and Bergmann, 1989). This early production feeds significant phytoplankton blooms later in the spring during advanced ice melt (e.g., Fortier et al., 2002), particularly if upwelling replenishes nutrients at the surface (e.g., Mundy et al., 2009). As well as forming the base of the Arctic Ocean food web, these under-ice phytoplankton blooms reduce dissolved $CO_2$ in the surface seawater, creating a potential for uptake of atmospheric carbon (Fransson et al., 2009). A transition towards earlier landfast ice breakup—as we observed in several areas of the CAA—may greatly affect the timing and magnitude of primary production in these areas and will also affect the exchange of climatologically important gases such as $CO_2$.

## CONCLUSIONS

Much of the Canadian marine Arctic sees the occurrence of landfast sea ice at some point in a given year. Areas north of 75˚ N and in the central CAA experience the most landfast sea-ice coverage both within and between years, while areas on the periphery of the CAA experience comparatively less. Within a sea-ice year, landfast sea ice persists over summer in the Western High Arctic in about two-thirds of years, and by November, the entire Canadian High Arctic is usually landfast. Landfast sea-ice onset is spatially and temporally variable; by the end of January, much of the sea ice in the central archipelago is landfast, while areas on the periphery of the CAA, like Amundsen Gulf and M'Clure Strait in the west and eastern Parry Channel and Prince Regent in the east, remain mobile for the duration of some years. Landfast sea-ice breakup is also spatially and temporally variable. Landfast ice breakup begins in the south about the beginning of June and moves towards the center of the CAA from the periphery and northwards for the duration of July and August. Greater variability in landfast breakup dates occurs where landfast sea ice occurs less often over the years.

Statistically significant regional trends in onset and breakup of landfast sea ice were found for the Beaufort Sea and CAA-East regions, showing that onset has been delayed by one to three weeks per decade, while breakup has advanced by more than a half a week per decade. Sub-regionally, the Alaska and Mackenzie sub-regions drive much of the trend toward later onset of landfast ice in the Beaufort region. Statistically significant trends towards later onset of landfast sea ice are also present in the Coronation-Maud, Western High Arctic, Eastern High Arctic and Admiralty Inlet sub-regions within the CAA. A significant trend towards earlier breakup is also occurring in the West Baffin Bay sub-region. Calculated trends in the total annual duration of landfast sea ice show that the landfast season is getting shorter in many areas of the Canadian Arctic. Areas of the Alaska, Mackenzie, Banks, Amundsen Mouth, Amundsen, Coronation-Maud, Kane Basin, and East Baffin Bay sub-regions are experiencing negative trends in landfast sea-ice duration, as are the Western and Eastern High Arctic regions. However, we find no significant trends in landfast ice duration in the interior of the Northwest Passage.

## ACKNOWLEDGEMENTS

Thanks to the Canadian Ice Service for making the CISDA freely available. Thanks to the Natural Sciences and Engineering Research Council, the ArcticNet Network of Centres of Excellence program and the Canada Research Chairs program for supporting this work. B.G.T. Else is supported by a Vanier Canada graduate scholarship. Thanks to V. Petrusevich and A. Komarov for Russian translations of the abstract and key words.

## REFERENCES

Agnew, T., and Howell, S. 2003. The use of operational ice charts for evaluating passive microwave ice concentration data. Atmosphere-Ocean 41(4):317–331.

Berkes, F., and Jolly, D. 2001. Adapting to climate change: Social-ecological resilience in a Canadian western Arctic community. Conservation Ecology 5(2): 18. [online] URL: http://www.consecol.org/vol5/iss2/art18/.

Brown, R.D., and Cote, P. 1992. Interannual variability of landfast ice thickness in the Canadian High Arctic, 1950–89. Arctic 45(3):273–284.

Buckley, J.R., Gammelsrød, T., Johannessen, J.A., Johannessen, O.M., and Røed, L.P. 1979. Upwelling: Oceanic structure at the edge of the Arctic ice pack in winter. Science 203(4376):165–167.

Carmack, E.C., and Chapman, D.C. 2003. Wind-driven shelf/basin exchange on an Arctic shelf: The joint roles of ice cover extent and shelf-break bathymetry. Geophysical Research Letters 30(14), 1778, doi:10.1029/2003GL017526.

Carmack, E.C., and Kulikov, E.A. 1998. Wind-forced upwelling and internal Kelvin wave generation in Mackenzie Canyon, Beaufort Sea. Journal of Geophysical Research 103(C9):18447–18458.

Clarke, A.J. 1978. On wind-driven quasi-geostrophic water movements near fast ice edges. Deep-Sea Research 25:41–51.

CIS (Canadian Ice Service). 2002. MANICE: Manual of standard procedures for observing and reporting ice conditions, 9th ed. Ottawa: Canadian Ice Service, Environment Canada.

Comiso, J.C. 2006. Abrupt decline in the Arctic winter sea ice cover. Geophysical Research Letters 33, L18504, doi:10.1029/2006GL027341.

Dean, K.G., Stringer, W.J., Ahlnäs, K., Searcy, C., and Weingartner, T. 1994. The influence of river discharge on the thawing of sea ice, Mackenzie River Delta: Albedo and temperature analysis. Polar Research 13:83–94.

Divine D.V., Korsnes, R., and Makshtas, A.P. 2004. Temporal and spatial variation of shore-fast ice in the Kara Sea. Continental Shelf Research 24(5):1717–1736.

Dmitrenko, I.A., Gribanov, V.A., Volkov, D.L., Kassens, H., and Eicken, H. 1999. Impact of river discharge on the fast ice extension in the Russian Arctic shelf area. In: Proceedings of the 15th International Conference on Port and Ocean Engineering under Arctic Conditions (POAC99), 23–27 August 1999, Helsinki University of Technology, Helsinki, Finland. Vol. 1:311–321.

Dumas, J., Carmack, E., and Melling, H. 2005. Climate change impacts on the Beaufort Shelf landfast ice. Cold Regions Science and Technology 42(1):41–51.

Ferguson, S.H., Taylor, M.K., and Messier, F. 2000. Influence of sea ice dynamics on habitat selection by polar bears. Ecology 81(3):761–772.

Flato, G.M., and Brown, R.D. 1996. Variability and climate sensitivity of landfast Arctic sea ice. Journal of Geophysical Research 101(C11):25767–25777.

Ford, J.D., Pearce, T., Gilligan, J., Smit, B., and Oakes, J. 2008. Climate change and hazards associated with ice use in northern Canada. Arctic, Antarctic, and Alpine Research 40(4):647–659, doi:10.1657//1523-0430(07-040)[FORD]2.0.CO;2.

Ford, J.D., Gough, W.A., Laidler, G.J., MacDonald, J., Irngaut, C., and Qrunnut, K. 2009. Sea ice, climate change, and community vulnerability in northern Foxe Basin, Canada. Climate Research 38(2):137–154.

Fortier, M., Fortier, L., Michel, C., and Legendre, L. 2002. Climatic and biological forcing of the vertical flux of biogenic particles under seasonal Arctic sea ice. Marine Ecology Progress Series 225:1–16, doi:10.3354/meps225001.

Fox, C., and Squire, V.A. 1990. Reflection and transmission characteristics at the edge of shore fast sea ice. Journal of Geophysical Research 95(C7):11629–11639, doi:10.1029/JC095iC07p11629.

Fransson, A., Chierici, M., and Nojiri, Y. 2009. New insights into the spatial variability of the surface water carbon dioxide in varying sea ice conditions in the Arctic Ocean. Continental Shelf Research 29(10):1317–1328.

Galley, R.J., Key, E., Barber, D.G., Hwang, B.J., and Ehn, J.K. 2008. Spatial and temporal variability of sea ice in the southern Beaufort Sea and Amundsen Gulf: 1980–2004. Journal of Geophysical Research 113, C05S95, doi:10.1029/2007JC004553.

Howell, S.E.L., Duguay, C.R., and Markus, T. 2009. Sea ice conditions and melt season duration variability within the Canadian Arctic Archipelago: 1979–2008. Geophysical Research Letters 36, L10502, doi:10.1029/2009GL037681.

Kinnard, C., Zdanowicz, C.M., Fisher, D.A., and Wake, C.P. 2006. Calibration of an ice core glaciochemical (sea-salt) record with sea-ice variability in the Canadian Arctic. Annals of Glaciology 44(1):383–390.

Kwok, R., Toudal-Pedersen, L., Gudmandsen, P., and Pang, S.S. 2010. Large sea ice outflow into Nares Strait in 2007. Geophysical Research Letters 37, L03502, doi:10.1029/2009GL041872.

Laidler, G.J., Ford, J.D., Gough, W.A., Ikummaq, T., Gagnon, A.S., Kowal, S., Qrunnut, K., and Irngaut, C. 2009. Travelling and hunting in a changing Arctic: Assessing Inuit vulnerability to sea ice change in Igloolik, Nunavut. Climatic Change 94(3-4):363–397.

Mahoney, A., Eicken, H., Graves Gaylord, A., and Shapiro, L. 2007. Alaska landfast sea ice: Links with bathymetry and atmospheric circulation. Journal of Geophysical Research 112, C02001, doi:10.1029/2006JC003559.

Marko, J.R. 1977. A satellite-based study of sea ice dynamics in the central Canadian Arctic Archipelago. Contractor Report Series 77-4. Sidney, British Columbia: Library, Institute of Ocean Sciences. 106 p.

Maykut, G.A. 1978. Energy exchange over young sea ice in the central Arctic. Journal of Geophysical Research 83(C7):3646–3658.

Melling, H. 2002. Sea ice of the northern Canadian Arctic Archipelago. Journal of Geophysical Research 107(C11), 3181, doi:10.1029/2001JC001102.

Mundy, C.J., Gosselin, M., Ehn, J., Gratton, Y., Rossnagel, A., Barber, D.G., Martin, J., et al. 2009. Contribution of under-ice primary production to an ice-edge upwelling phytoplankton bloom in the Canadian Beaufort Sea. Geophysical Research Letters 36, L17601, doi:10.1029/2009gl038837.

O'Brien, M.C., Macdonald, R.W., Melling, H., and Iseki, K. 2006. Particle fluxes and geochemistry on the Canadian Beaufort Shelf: Implications for sediment transport and deposition. Continental Shelf Research 26(1):41–81.

Perovich, D.K., and Richter-Menge, J.A. 2009. Loss of sea ice in the Arctic. Annual Review of Marine Science 1:417–441.

Perovich, D.K., Richter-Menge, J.A., Jones, K.F., and Light, B. 2008. Sunlight, water and ice: Extreme Arctic sea ice melt during the summer of 2007. Geophysical Research Letters 35, L11501, doi:10.1029/2008GL034007.

Persson, P.O.G., Fairall, C.W., Andreas, E.L., Guest, P.S., and Perovich, D.K. 2002. Measurements near the Atmospheric Surface Flux Group tower at SHEBA: Near-surface conditions and surface energy budget. Journal of Geophysical Research 107(C10), 8045, doi:10.1029/2000JC000705.

Pickart, R.S., Moore, G.W.K., Torres, D.J., Fratantoni, P.S., Goldsmith, R.A., and Yang, J. 2009. Upwelling on the continental slope of the Alaskan Beaufort Sea: Storms, ice, and oceanographic response. Journal of Geophysical Research 114, C00A13, doi:10.1029/2008JC005009.

Polyakov, I.V., Alekseev, G.V., Bekryaev, R.V., Bhatt, U.S., Colony, R., Johnson, M.A., Karklin, V.P., Walsh, D., and Yulin, A.V. 2003. Long-term ice variability in Arctic marginal seas. Journal of Climate 16:2078–2085.

Rothrock, D.A., and Zhang, J. 2005. Arctic Ocean sea ice volume: What explains its recent depletion? Journal of Geophysical Research, 110, C01002, doi:10.1029/2004JC002282.

Rothrock, D.A., Yu, Y., and Maykut, G.A. 1999. Thinning of the Arctic sea-ice cover. Geophysical Research Letters 26(23):3469–3472, doi:10.1029/1999GL010863.

Smith, T.C., and Hammill, M.O. 1981. Ecology of the ringed seal, *Phoca hispida*, in its fast ice breeding habitat. Canadian Journal of Zoology 59(6):966–981.

Squire, V.A. 1993. The breakup of shore fast sea ice. Cold Regions Science and Technology 21(3):211–218.

Squire, V.A., Dugan, J.P., Wadhams, P., Rottier, P., and Liu, A.K. 1995. Of ocean waves and sea ice. Annual Review of Fluid Mechanics 27:115–168.

Stewart, E.J., Howell, S.E.L., Draper, D., Yackel, J., and Tivy, A. 2007. Sea ice in Canada's Arctic: Implications for cruise tourism. Arctic 60(4):370–380.

Stroeve, J., Holland, M.M., Meier, W., Scambos, T., and Serreze, M. 2007. Arctic sea ice decline: Faster than forecast. Geophysical Research Letters 34, L09501, doi:10.1029/2007GL029703.

Tivy, A., Howell, S.E.L., Alt, B., McCourt, S., Chagnon, R., Crocker, G., Carrieres, T., and Yackel, J.J. 2011. Trends and variability in summer sea ice cover in the Canadian Arctic based on the Canadian Ice Service digital archive, 1960–2008 and 1968–2008. Journal of Geophysical Research 116, C03007, doi:10.1029/2009JC005855.

Welch, H.E., and Bergmann, M.A. 1989. Seasonal development of ice algae and its prediction from environmental factors near Resolute, N.W.T., Canada. Canadian Journal of Fisheries and Aquatic Sciences 46(10):1793–1804.

Wohlleben, T., Tivy, A., and Galley, R. 2010. An investigation into the anomalous sea ice conditions in Lincoln Sea and Nares Strait: 2007, 2009 and 2010. Presented at the International Symposium on Sea Ice in the Physical and Biogeochemical System, International Glaciological Society, 31 May–4 June, Tromso, Norway.