Chapter 10
Factors Contributing to Recent Arctic Ice Shelf Losses

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Abstract A review of historical literature and remote sensing imagery indicates that the ice shelves of northern Ellesmere Island have undergone losses during the 1930s/1940s to 1960s, and particularly since the start of the twenty-first century. These losses have occurred due to a variety of different mechanisms, some of which have resulted in long-term reductions in ice shelf thickness and stability (e.g., warming air temperatures, warming ocean temperatures, negative surface and basal mass balance, reductions in glacier inputs), while others have been more important in defining the exact time at which a pre-weakened ice shelf has undergone calving (e.g., presence of open water at ice shelf terminus, loss of adjacent multiyear landfast sea ice, reductions in nearby epishelf lake and fiord ice cover). While no single mechanism can be isolated, it is clear that they have all contributed to the marked recent losses of Arctic ice shelves, and that the outlook for the future survival of these features is poor.

Keywords Ice shelf • Calving • Multiyear landfast sea ice • Mass balance • Climate warming • Glaciers

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10.1 Introduction

There have been rapid changes to the Arctic cryosphere over the past decade, with increased melt rates on Canadian Arctic ice caps (Fisher et al. 2012; Sharp et al. 2011), a strongly negative mass balance for the Greenland Ice Sheet (Box 2013), an acceleration and increase in mass loss from many Greenland outlet glaciers (Rignot et al. 2011; Schrama and Wouters 2011), and rapid reductions in sea ice area, age and thickness (Kwok and Rothrock 2009; Yu et al. 2014; Simmonds 2015). Over this same period, there have also been dramatic changes to the ice shelves of northern Ellesmere Island, Nunavut, Canada, such as the complete loss of the 87 km^2 Ayles Ice Shelf in August 2005 (Copland et al. 2007), complete loss of the 50 km^2 Markham Ice Shelf in summer 2008 (Mueller et al. 2008), and ~90% loss of the ~180 km^2 Serson Ice Shelf between 2008 and 2011 (Table 10.1). The ice shelves in this region reduced in number from six to three between 2005 and 2012, with a decrease in area from 1043 km^2 at the start of summer 2005 to ~500 km^2 at the end of summer 2015 (Mueller et al. 2017). These ice shelf losses have produced a large number of ice islands that have typically drifted westward after formation into the

Table 10.1 Timing and size of major calving events from the Ellesmere Island ice shelves, 2000–2012

Ice Shelf	Date	Event	Area loss (km^2)	Area after loss (km^2)	Reference(s)
Ward Hunt	2000–2002	Calving	6	436	Mueller et al. 2003
	July–August 2008	Calving	42	394	Mueller et al. 2008
	August 2010	Calving	54	340	This study
	August 2011	Split in two	39	301	Mueller et al. 2017
	August 2012	Calving from western side	6	295	This study
Ayles	August 13, 2005	Complete loss	87	0	Copland et al. 2007
Markham	August 7–12, 2008	Complete loss	50	0	Mueller et al. 2008
Petersen	August 8–18, 2005	Calving	8.0	41	Pope et al. 2012; White 2012
	August 2008	Calving	9.0	32	White 2012
	Summer 2011	Calving	5.5	25	White 2012
	August 2012	Calving	5.5	19	White 2012
Serson	July 29–31, 2008	Calving	122	77	Mueller et al. 2008
	August 1–8, 2011	Calving	45	32	This study
Milne[a]	September 2009	–	–	205	Mortimer et al. 2012

Adapted from Copland (2009) and White (2012)

[a] Milne Ice Shelf did not experience any significant changes over the period 2000–2012 (Mortimer et al. 2012)

interior parts of the western Queen Elizabeth Islands or into the Beaufort Sea (Van Wychen and Copland 2017), where they may pose a significant risk to offshore infrastructure and shipping (Fuglem and Jordaan 2017).

To help understand the driving mechanisms behind recent ice shelf losses, it is useful to consider the location and timing of past calving events. In this chapter, calving events are defined as the partial or complete loss of an ice shelf, and can typically be identified easily in remote sensing imagery. They differ from breakup events, which represent the fracturing of an ice shelf, and which may occur in situ without the loss of ice shelf area. Due to the difficulty of detecting small-scale breakup events with remote sensing imagery, most of the discussion here is focused on calving.

Frequent repeat imaging using satellite sensors such as the Moderate Resolution Imaging Spectroradiometer (MODIS; ~250 m resolution), together with Synthetic Aperture Radar (SAR) wide swath images from sensors such as Radarsat and Envisat (~100 m resolution), has enabled detailed reconstructions of the timing and patterns of ice shelf calving events since the early 2000s. This imagery indicates that ice shelf losses have occurred from embayments across northern Ellesmere Island (Table 10.1; Fig. 10.1). Indeed, five out of the six ice shelves present at the start of the twenty-first century lost substantial area between 2000 and 2012. The only ice shelf which did not experience a significant change in area over this time was the Milne, which measured 206 km^2 in 2001 and 205 km^2 in 2009 (Mortimer et al. 2012).

Historical records from early explorers such as Lt. Aldrich in 1876 (Nares 1878) and Robert Peary in 1906 (Peary 1907) described a continual ice shelf fringe along the coast of northern Ellesmere Island, with an estimated area of 8900 km^2 at the start of the twentieth century (Vincent et al. 2001). For example, Nares (1878) described the ice shelves as permanent 'hummocky' ice with a rolling surface, and for the Ward Hunt Ice Shelf stated that '*The hummocks do not come in close to Ward Hunt Island… The line of hummocks is between five and six miles off, and does not seem to differ from those farther east.*'. Similarly, for Ayles Fiord, '*The actual line of hummocky ice is still about two miles from shore*'. As of 2015 this fringe is no longer continuous, and instead ice shelves are present in only three fiords (Petersen, Milne and Disraeli/Ward Hunt), totalling ~500 km^2 (see Mueller et al. 2017 for a full review). The twentieth century ice shelf losses were spatially extensive, both in terms of a reduction in the distance that ice shelves extended northwards into the Arctic Ocean, and longitudinally in terms of their distribution across northern Ellesmere Island.

Chronologically, the ice shelves of northern Ellesmere Island have lost area during two main periods: (1) the 1930s/1940s to 1960s (start date is poorly defined due to paucity of data); (2) since the start of the twenty-first century (particularly 2002–2012). During the earlier period, extensive ice islands were produced as the ice shelves calved, such as the loss of the >1300 km^2 ice shelf in Yelverton Bay between the mid-1930s and mid-1940s, which produced ice islands T-1, T-2 and T-3 (Koenig et al. 1952; Jeffries 1987; Pope et al. 2012). These ice islands were the largest ever observed in the Arctic Ocean, with Koenig et al. (1952) stating that T-1 had an area

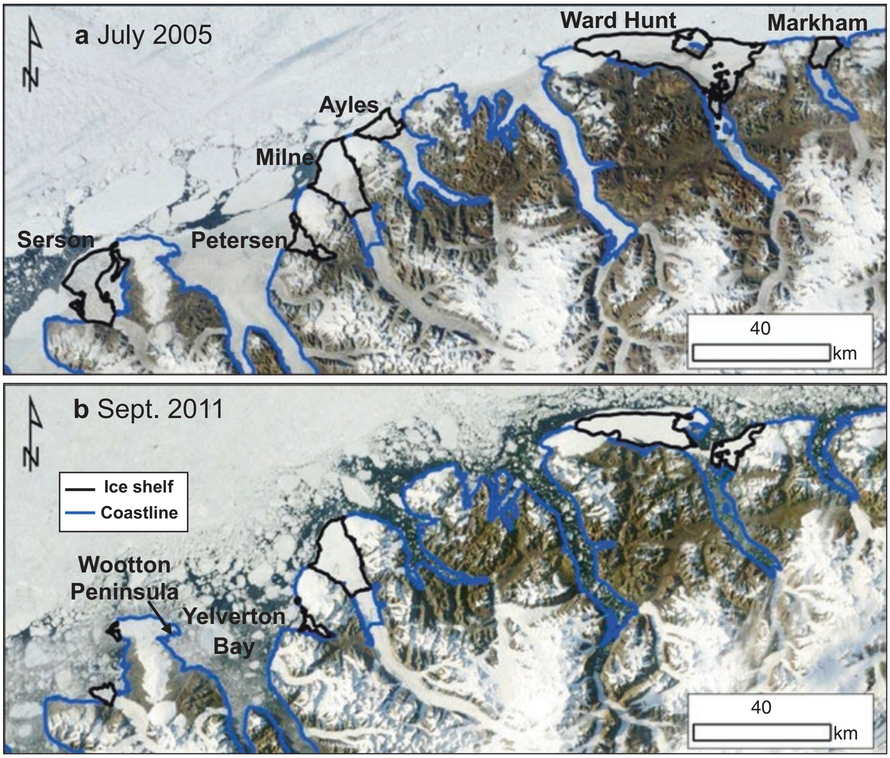

Fig. 10.1 Extent of ice shelves across northern Ellesmere Island in: (**a**) July 2005, and (**b**) September 2011. Losses between these dates have been widespread, with the complete loss of the Serson, Ayles and Markham ice shelves, and substantial reductions in area of the Ward Hunt and Petersen ice shelves (see Table 10.1 for details) (MODIS base imagery courtesy of the Rapid Response Project at NASA/GSFC)

of >200 square nautical miles (nm) (>687 km^2), while T-2 measured 17 × 18 nm and had an area of ~300 nm^2 (1030 km^2). Other evidence for ice shelf losses at this time comes from widespread observations of ice islands in aerial photography and from military flights, including the identification of >28 ice islands by Koenig et al. (1952) and an additional 31 ice islands by Montgomery (1952) (see Van Wychen and Copland 2017 for a full review). After the 1960s the ice shelves of northern Ellesmere Island were generally stable until the start of the twenty-first century, with the exception of relatively small losses from the Ward Hunt Ice Shelf of 35–40 km^2 from 1980 to 1982, and ~40 km^2 in 1982–1983 (Jeffries and Serson 1983). Since the start of the twenty-first century, ice shelf losses have been more extensive again, especially in the summers of 2005, 2008 and 2011, with the total remaining area in 2012 approximately half of the 1043 km^2 present in 2005 (Table 10.1).

Given the patterns described above, the large spatial extent of ice shelf losses implies that contributory factor(s) were likely acting at a regional, and not just local, scale. However, the contributing factor(s) did not occur at a constant rate as losses were dominant in the 1940s–1960s and since the start of the twenty-first century. With these constraints in mind, the following review addresses the main mechanisms that have likely been responsible for the ice shelf losses. This information is required to understand and predict the fate of the remaining Arctic ice shelves, and here we use a combination of field measurements, remote sensing observations and a review of existing literature to present conclusions about the dominant factors which have caused ice shelf losses. Most discussion focuses on calving events that have occurred over the period 2002–2012 due to the improved availability of data from this period compared to earlier times, although discussion of earlier losses is also included where relevant.

10.2 Climate

Major climate assessments have reported significant temperature increases in the Arctic over the past few decades, with the Arctic warming twice as fast as the rest of the planet since 1980, and warming mainly focused in the winter (AMAP 2012). At Eureka, the closest weather station to the Ellesmere ice shelves (~200 km south), Lesins et al. (2010) analyzed climate records collected between 1954 and 2007. The mean annual surface air temperature warmed 3.2°C since 1972, with summer exhibiting the least change of any season. There was also a 10% increase in precipitation since 1961, dominated by changes in the spring, summer and fall.

To understand changes occurring at the ice shelves, Copland et al. (2007) undertook NCEP/NCAR climate reanalysis of 1000 mbar daily air temperatures for the Ayles Ice Shelf. This indicated a mean annual warming of 0.37°C decade^{-1} between 1948 and 2006, for a total increase of ~2.1°C. This warming was not evenly distributed throughout the year, with particularly strong warming in the fall, winter and spring, but no significant trend in the summer. Mueller et al. (2009) also found similar patterns for regions adjacent to the Ward Hunt Ice Shelf, with mean annual warming of 0.48°C decade^{-1} between 1948 and 2007, and greatest increases in the fall (0.70°C decade^{-1}) and winter (0.68°C decade^{-1}), less in the spring (0.42°C decade^{-1}), and no statistically significant trend in the summer (0.08°C decade^{-1}). In terms of the energy available for ice shelf melting, this can be expressed in terms of positive degree days (PDDs), with Copland et al. (2007) finding that a threshold of >200 PDDs year^{-1} appeared to relate to periods of enhanced ice shelf calving, with this level reached during most years between 1948 and 1963, and since the mid-1990s. Copland et al. (2007) also found that there has been a strongly significant reduction in the number of freezing degree days (FDDs) since 1948, and particularly since the 1990s, with 2005 having the lowest on record (5472 FDDs year^{-1}, compared to the long-term average of 6370 FDDs year^{-1}). This lack of winter cold means that the ice shelves are less able to recover from summer melt, and likely experience less basal freeze-on than before.

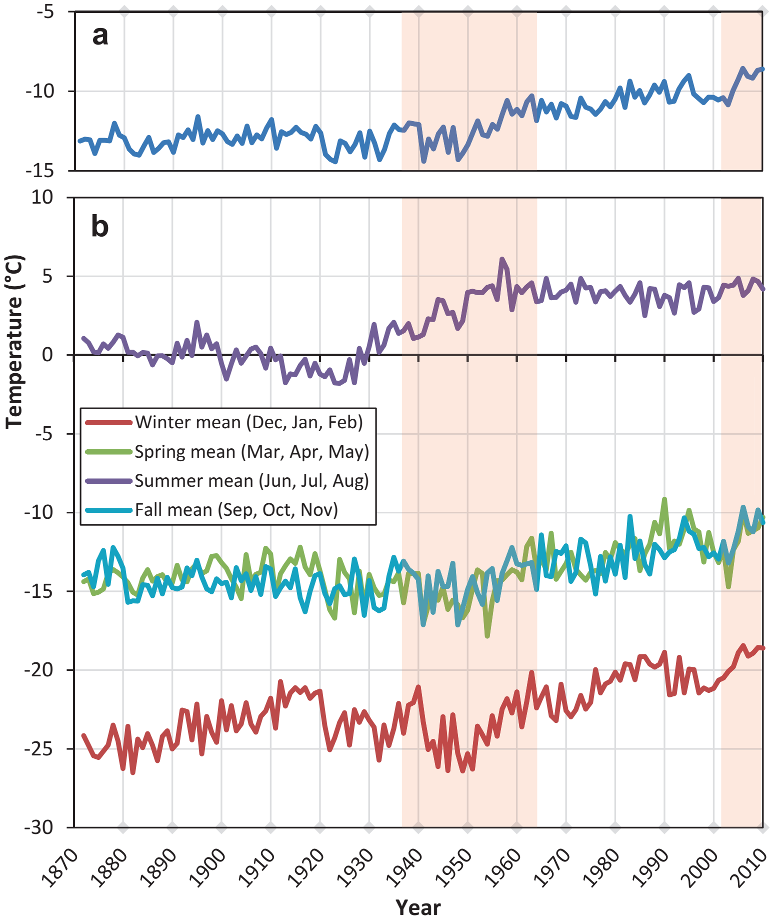

Fig. 10.2 Surface air temperature trends from 1870 to 2010 for northern Ellesmere Island (82.5°N, 82.0°W) derived from the Twentieth Century Reanalysis project (V2) (http://www.esrl.noaa.gov/psd/data/gridded/data.20thC_ReanV2.html): (**a**) Mean annual air temperatures; (**b**) Seasonal air temperatures. Main ice shelf calving periods indicated by *pink shading*

The completion of the Twentieth Century Reanalysis (V2) project (Compo et al. 2011) allows for the assessment of long-term temperature patterns for northern Ellesmere Island for the first time. Based on the grid cell centered at 82.5°N, 82.0°W (near the centre of the Petersen Ice Shelf), mean monthly air temperatures at the 1000 mbar level for the period January 1870 to December 2010 were retrieved from the NOAA Earth System Laboratory Website (http://www.esrl.noaa.gov/psd/data/gridded/data.20thC_ReanV2.html) (Fig. 10.2). In terms of mean annual temperatures, there was generally little change between 1870 and the late 1940s, but then a rapid warming occurred during the 1950s, followed by a more gradual warming from the 1960s to 1990s (Fig. 10.2a), consistent with the climate patterns described above. Temperatures have increased rapidly since 2005, with mean annual temperatures over 2006–2010 (−8.8°C) almost 5°C warmer than over the period 1946–1950 (−13.5°C). Broken down by season, summer temperatures warmed by >5°C between the early 1930s and late 1950s, but showed generally little variability before or after that (Fig. 10.2b). The 1930s–1950s summer warming preceded that observed in other seasons, with sustained winter warming only observed since the 1950s. Warming over the past decade has been primarily driven by increases in winter air temperatures, although fall and spring increases have also been apparent. Mean winter temperatures rose from −25.2°C between 1946 and 1950, to −18.7°C between 2006 and 2010. These warming patterns align well with the main periods of ice shelf losses in the 1940s–1960s and 2000s. It appears that summer warming was particularly important during the earlier period, while winter warming (and to a lesser extent, fall and spring warming) was more dominant over the past decade. However, White et al. (2015a) also demonstrated that recent calving events from the Petersen Ice Shelf (in 2005, 2008, 2011, and 2012) occurred during summers with record-breaking mean summer temperatures.

Given the above review it seems likely that there has been a connection between rising air temperatures and ice shelf losses over the past century or so. However, it is unclear as to which ice shelf physical characteristics have been most impacted by these temperature changes. This information is important to understand the exact causes of the losses and to understand how the ice shelves may evolve in the future. This is addressed in the remainder of this chapter.

10.3 Changes in Glacier Inputs

Canadian ice shelves are comprised of ice from several different sources, including meteoric ice that has formed from snow and rain deposition directly on their surface, marine ice formed in situ and added from lateral and basal freeze-on, and glacier ice derived from glacier flow into their margins (Mueller et al. 2006). Of the six ice shelves which were present in 2000, the Ayles, Milne, Petersen and Serson ice shelves received appreciable glacier input. For these ice shelves an important question is whether the glacier inputs have changed over time, as glaciers typically reduce in area, thickness and velocity in response to long term negative mass balance conditions (Thomson and Copland 2017). Information about the changes in glacier inputs for the Ayles, Milne and Petersen ice shelves is therefore reviewed below.

For the Ayles Ice Shelf, it is clear from air photos and satellite imagery that a major glacier which fed the rear of the ice shelf in 1959 had become completely disconnected by the early 2000s (Fig. 10.3). A report from an overflight in April 1966 (Hattersley-Smith 1967) suggests that this likely occurred in the mid-1960s, although the exact timing of this disconnection is unknown due to the lack of image data. It is likely that this glacier previously provided one of the biggest mass inputs to the ice shelf, and Copland et al. (2007) argued that the loss of this glacier input

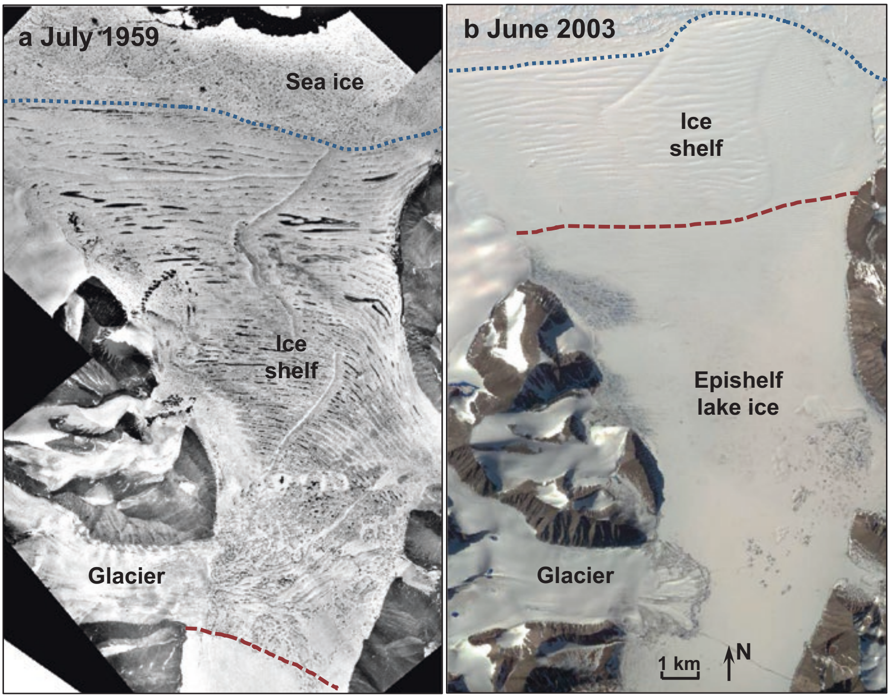

Fig. 10.3 Comparison of the Ayles Ice Shelf between: (**a**) July 1959 air photo (©Her Majesty the Queen in Right of Canada), and (**b**) June 2003 Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) satellite image. *Blue dotted line* indicates front of ice shelf, and *red dashed line* shows the rear. In the 1960s the front part of the ice shelf calved, and most of the remaining ice moved ~5 km northwards before refreezing in place at the head of the fiord (Jeffries 1986). Note how the main glacier input in 1959 had disconnected from the ice shelf by 2003; this disconnection likely occurred in the mid-1960s (Hattersley-Smith 1967)

likely contributed to the long-term negative mass balance of the Ayles Ice Shelf prior to its calving in August 2005.

Of all past and current Canadian ice shelves, the Milne Ice Shelf is the one that has received greatest glacier inputs. Mortimer (2011) used air photos and satellite imagery from 1950, 1959, 1984, 1993, 2001 and 2009 to identify and monitor changes in glacier inputs to the ice shelf over time. Five tributary glaciers terminated on the ice shelf in 1950, with Glaciers 1, 2 and 6 extending towards the ice shelf centre by at least 4.5, 2.5 and 1.5 km, respectively (Fig. 10.4a). By 1984, Glacier 1 terminated near the fiord sidewall, leaving a large remnant glacier tongue ~5 km long encompassed within the ice shelf. Air photo coverage for 1984 did not include the terminus of Glacier 3, but by 1993 it had retreated by ~3 km compared to 1959 (Fig. 10.4b), with its terminus separated from the ice shelf by an ice dammed lake. Further retreat of all tributary glaciers occurred between 1993 and 2009, with the glaciers nearest the rear of the ice shelf (Glaciers 3 and 4) retreating farthest, compared to those near the ice shelf front (Glaciers 1, 2 and 6). Field observations

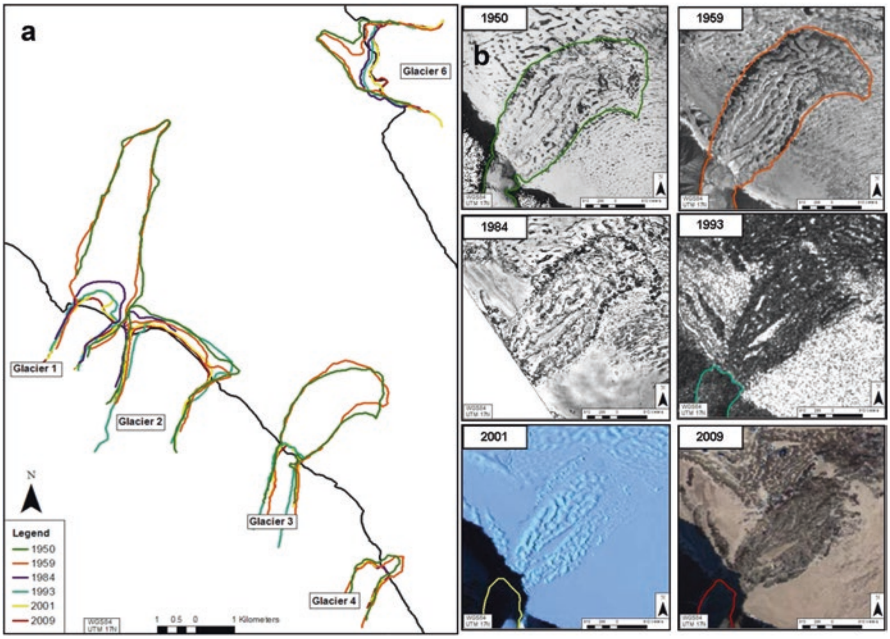

Fig. 10.4 (**a**) Changes in extent of the five main tributary glaciers flowing into the Milne Ice Shelf, 1950–2009; (**b**) Changes in the terminus position of Glacier 3 delineated from historical air photos (1950, 1959, 1984) and satellite imagery (1993: European Remote-Sensing Satellite-1 (ERS-1); 2001 and 2009: ASTER) (From Mortimer (2011))

in May 2009 indicated that Glacier 4 is now a hanging glacier, entirely disconnected from the ice shelf, whereas Glacier 1 still terminated on the ice shelf (Fig. 10.4a). Overall, all glaciers which provided direct input to the Milne Ice Shelf have retreated since 1950, with the largest retreat observed between 1959 and 1984. Mortimer et al. (2012) calculated the inflow from the last remaining tributary glacier in 2011 (Glacier 2; Fig. 10.4a) to be 0.048 m water equivalent (w.e.) year^{-1} averaged over the 2009 ice shelf area. This suggests that current glacier ice input compensates for <20% of the observed thinning rate of 0.26 m w.e. year^{-1} over the period 1981–2008/2009 (see Sect. 10.4 for details), and is unable to balance current mass losses. Glacier inputs also tend to be concentrated in ice tongues on the Milne Ice Shelf, meaning that many regions of the ice shelf receive effectively no glacier input to replace mass losses.

On the Petersen Ice Shelf, White et al. (2015a) recorded changes of the glaciers providing input to the ice shelf over the past 60 years. In 1959, three glaciers flowed into the ice shelf: one from the south (Fig. 10.5b), one from the northwest (not shown), and one from the north (not shown). These glaciers remained stable until the 2000s, with the northwest glacier advancing by ~250 m between 1959 and 1999. Major changes occurred to the southern glacier after the mid-2000s, with the glacier disconnecting from the ice shelf between 2007 and 2008 (Fig. 10.5c, d). Areas of ice

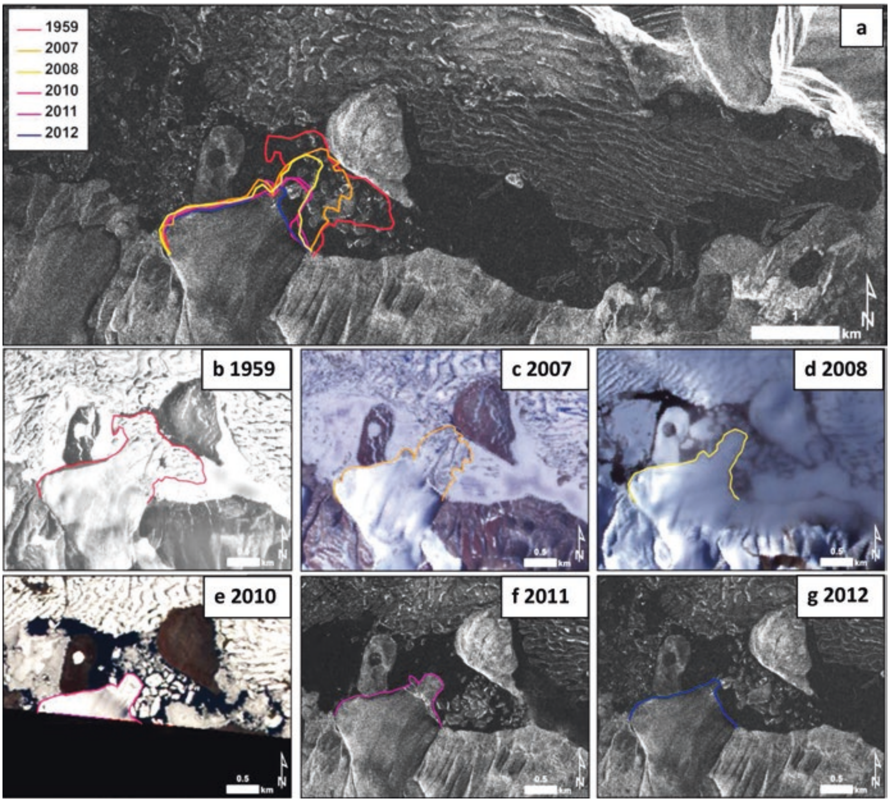

Fig. 10.5 (**a**) Temporal changes in the extent of the tributary glacier flowing from the southern coast into Petersen Bay, 1959–2012 (base image: Ultrafine Wide Radarsat-2 HH, February 3, 2012); (**b**) Aerial photography from August 13, 1959; (**c**) ASTER L1B scene acquired July 7, 2007; (**d**) ASTER L1B scene acquired August 22, 2008; (**e**) ASTER L1B scene acquired July 19, 2010; (**f**) Ultrafine Radarsat-2 HH scene acquired July 19, 2011; (**g**) Ultrafine Wide Radarsat-2 HH scene acquired February 3, 2012 (RADARSAT-2 Data and Products © MacDonald, Dettwiler and Associates Ltd. (2012), All Rights Reserved. From White (2012))

shelf which existed adjacent to this glacier in 1959 disintegrated, and produced new icebergs during an open water event in August 2008 (Fig. 10.5d). Further fracturing of the glacier terminus occurred between 2010 and 2012 during other open water events (Fig. 10.5e–g), with a large area of sea ice and icebergs now present between the glacier terminus and remaining ice shelf. The southern glacier therefore no longer provides any input to the ice shelf, although speckle tracking of Radarsat-2 scenes indicates that the northwestern glacier currently flows at ~20 m year^{-1} where it enters the ice shelf, and the northern glacier flows at ~7 m year^{-1} at the ice shelf boundary (White et al. 2015a). When combined with ice thickness measurements determined from ground-penetrating radar, White et al. (2015a) calculated that these glaciers currently provide a mass input of 0.07–0.12 m w.e. year^{-1} to the Petersen Ice Shelf when averaged over the February 2012 ice shelf area. However, as described above for the Milne Ice Shelf, the fact that glacier inputs are concentrated close to their source means that many parts of the ice shelf currently receive essentially no contribution from glacier ice.

10.4 In Situ Mass Balance

Given the strong evidence for climate warming and reductions in glacier input to the Ellesmere Island ice shelves over time, a related question is whether there have also been changes in their in situ mass balance. Long-term mass balance measurements on the ice shelves are few, but Braun (2017) provides a comprehensive review of measurements conducted on the Ward Hunt Ice Shelf and adjacent Ward Hunt Ice Rise since the 1950s (Fig. 10.1). The ice rise sits at a higher elevation than the adjacent ice shelf, is ~40–100 m thick, and is thought to have formed from the grounding of the ice shelf when it thickened over the past ~1500 years (Braun et al. 2004). Starting in 1959, >100 ablation stakes were installed on these ice masses, and measured annually until 1986 and infrequently since then. In 2002, a total of 14 new ablation stakes were installed on the ice rise, and in 2004 this network was expanded by the addition of a total of 30 stakes at 5 different locations on the Ward Hunt Ice Shelf (Braun et al. 2004; Mueller and Vincent 2006). These measurements indicate that winter snow accumulation remained relatively constant between 1952 and 2008, but that there was much more variability in summer ablation (Braun 2017). Negative mass balance years have dominated since the 1950s, particularly on the ice shelf compared to the ice rise, with cumulative surface mass losses on the ice shelf of ~6.3 m w.e., or a mean loss of 0.11 m w.e. year^{-1}, between 1952 and 2007. These losses are strongly influenced by particular years, however, such as a loss of 0.54 m w.e. in 2003 that accounted for half of total mass losses of 1.03 m w.e. between 1989 and 2003.

Mass balance measurements only provide information pertaining to mass changes at the ice shelf surface, whereas the effect of basal freeze-on or melting can also be important. Information concerning mass exchanges at the base of the Ward Hunt Ice Shelf suggest that basal freeze-on (accretion) was roughly equivalent to the negative surface mass balances observed between 1952 and 1982, leading to a stable ice thickness over this period (Braun 2017). Considerable thinning started in the early 1990s, however, with Vincent et al. (2001) and Mueller et al. (2003) using measurements of freeboard and changes in the depth of a freshwater layer trapped behind the ice shelf to indicate that the minimum ice shelf thickness reduced by up to ~50% (to an average of ~25 m) in the 1990s. Given that surface mass losses over this period were much less than the observed thinning, this suggests that basal losses have been much more significant than surface losses at the Ward Hunt Ice Shelf in the recent past (Braun 2017). Evidence for basal thinning is further supported by the fact that a major warming episode occurred in the Canadian portion of the Arctic Ocean in the 1990s that was much larger than any other event since the late 1940s (Gerdes et al. 2003). There is also evidence that another warm anomaly occurred in the Arctic Ocean around 2005–2007 (Beszczynska-Möller et al. 2012), which was even warmer than the event in the mid-1990s, and likely contributed to a 0.28–0.35 m loss in thickness of Arctic sea ice (Polyakov et al. 2010). These ocean warmings seem to mainly originate from an increase in heat flux through Fram Strait (Beszczynska-Möller et al. 2012). The impacts of long-term thinning became obvious when the central part of the Ward Hunt Ice Shelf fractured between 2000 and 2002 (Mueller et al. 2003), and then completely disintegrated in summer 2011, leaving the ice shelf separated into two individual parts for the first time in recorded history. There are no glacier inputs into the Ward Hunt Ice Shelf, so glacier changes can be ruled out as a cause of the observed losses.

On the Milne Ice Shelf, Mortimer et al. (2012) used 250 MHz ground-penetrating radar surveys in 2008/2009 to quantify changes in the thickness and volume of the ice shelf since measurements in 1981 by Prager (1983) and Narod et al. (1988). For direct line comparisons along a 7.5 km transect near the ice shelf front, there was a total average loss of 2.63 ± 2.47 m, equivalent to a mean specific mass balance of -0.085 ± 0.079 m w.e. year^{-1}. However, there was large spatial variability along the transect, with substantial thinning along the ~5 km seaward part of it (up to 9.69 m loss averaged over a 1 km distance), but some thickening in areas furthest inland (up to 5.01 m gain averaged over a 1 km distance). For the ice shelf as a whole, Mortimer et al. (2012) found that thinning dominated, with an average thinning of 8.1 ± 2.8 m (0.26 ± 0.09 m w.e. year^{-1}) over the period 1981–2008/2009, equating to a reduction in volume of 13% (1.5 ± 0.73 km^3 w.e.). There are no direct surface mass balance measurements for the Milne Ice Shelf over this period, but Mortimer et al. (2012) calculated that 73% of the measured thinning can be attributed to basal melt if it is assumed that the 1989–2003 surface mass loss rates of 0.07 m year^{-1} measured on the Ward Hunt Ice Shelf (Braun et al. 2004) can be applied to the Milne Ice Shelf.

The only other Canadian ice shelf with recent surface mass balance measurements is the Petersen Ice Shelf. The record is limited, with White (2012) reporting mean surface ablation of 1.18 m w.e. year^{-1} from measurements at two stakes over the period May 2011 to May 2012. Ice coring on and around the Petersen Ice Shelf provided no evidence for basal freeze-on in the recent past, while the glacier inputs described above (Sect. 10.3) compensated for <10% of this mass loss. It is difficult to draw conclusions about long-term trends based on a single year of mass balance data, but given the 2011 mean ice thickness of the Petersen Ice Shelf of 29 m, White et al. (2015a) predicted that it is unlikely to survive for more than a couple of decades given current mass balance conditions.

10.5 Sea Ice Changes

One of the most widely reported changes to the cryosphere over the past few decades has been the widespread loss of Arctic sea ice. Average Arctic sea ice extent is currently about 30% less than it was over the period 1979–2000 (AMAP 2012), with almost every September minimum extent of the past decade falling below the

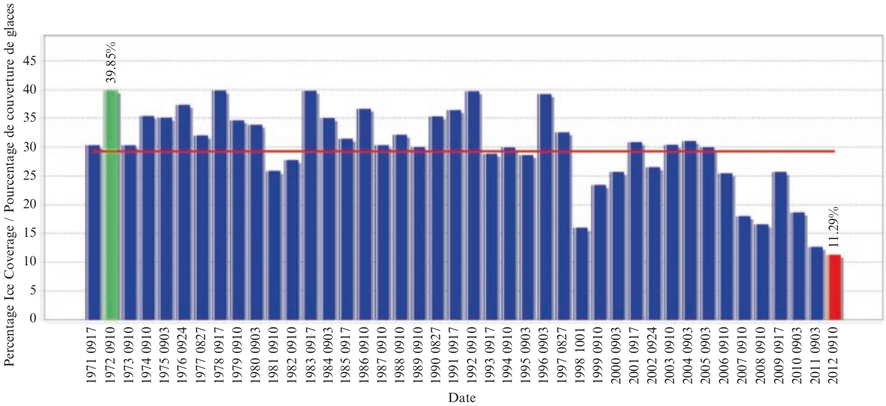

Fig. 10.6 Minimum sea ice coverage (%) over the Canadian Arctic, 1971–2012. *Red line* = 1981–2010 average (29.3%); *Green bar* = record maximum (1972, 39.9%); *Red bar* = record minimum (2012, 11.3%) (Source: Canadian Ice Service IceGraph v2.5 (http://iceweb1.cis.ec.gc.ca/IceGraph20))

long-term average. For example, the average September pan-Arctic minimum extent between 1981 and 2010 was 6.28×10^6 km^2, compared to the record minimum in September 2012 of 3.41×10^6 km^2 (http://nsidc.org/data/seaice_index/). The precise rate of Arctic sea ice decline is sensitive to the averaging period and method of calculation, but the most widely agreed upon rate is −11.5% decade^{-1} for September minimum extent between 1979 and 2012 (Wohlleben et al. 2013). In parallel with reductions in sea ice extent, there have also been marked reductions in average sea ice thickness and age. For example, Maslanik et al. (2011) reported a reduction in the proportion of multiyear sea ice in the Arctic from ~75% in the mid-1980s to ~45% in 2011. They also reported that the multiyear ice pack is becoming younger on average, with the proportion of ice >5 years old reducing from 50% to 10% over the same period. In terms of thickness, the mean winter thickness reduced from 3.64 m in 1980 to 1.89 m in winter 2008 for the central part of the Arctic Ocean (Kwok and Rothrock 2009).

Within the Canadian Arctic, recent sea ice losses have been dramatic. The minimum annual ice coverage derived from the Canadian Ice Service IceGraph tool has been markedly lower than the long-term average over the past decade (Fig. 10.6). In particular, 2012 reached a record low of 11.3% ice coverage in the Canadian Arctic, compared to the 1981–2010 normal minimum coverage of 29.3%. In terms of the significance of these changes for the Ellesmere Island ice shelves, it is clear that sea ice helps to stabilize ice shelves and tidewater glaciers (Reeh et al. 2001; Scambos et al. 2004; Williamson et al. 2008). The most detailed study to date of the loss of an Arctic ice shelf by Copland et al. (2007) found that there was a strong relationship between the timing of sea ice changes along the coastline of northern Ellesmere Island and the loss of the Ayles Ice Shelf. In particular, a semi-permanent fringe of multiyear landfast sea ice (MLSI) was lost from the front of the Ayles Ice Shelf in the ~2 weeks prior to its calving on August 13, 2005, accompanied by a period of open water along this coastline. A review of 179 SAR satellite scenes of this region from 1992 to 2005 by Copland et al. (2007) indicated that such sea ice conditions were unusual, with open water only observed in 7% of the SAR scenes and no evidence for loss of the MLSI fringe prior to August 2005. These observations align with the findings of Yu et al. (2014), who analyzed changes in the distribution of landfast sea ice across the Arctic over the period 1976–2007. They found significant reductions in the amount of winter landfast sea ice in almost all regions, with losses along the northern portion of the Canadian Arctic Archipelago (CAA) being among the largest of any location, changing at a rate of -19.7% decade^{-1}, compared to the Northern Hemisphere average of -6.7% decade^{-1}. This has been accompanied by a reduction in length of the landfast sea ice season for the northern CAA, with Yu et al. (2014) reporting change at a rate of -1.7 week decade^{-1} (-4.2% decade^{-1}) between 1977 and 2007. This aligns with an increase in the movement of multiyear sea ice from the Arctic Ocean to the CAA since 2005, most likely due to an increase in open water within the CAA which has provided more space for inflow to occur (Howell et al. 2013).

Copland et al. (2007) reported on the loss of >1000 km^2 of MLSI in Yelverton Bay in August 2005, both before and after the Ayles Ice Shelf losses. Pope et al. (2012) expanded on this study to reconstruct the long-term history of ice changes in Yelverton Bay and Inlet, and reported that MLSI losses also occurred in summer 2008 and summer 2010, with no multiyear ice cover left in this region at the end of summer 2010 for the first time in the historical record. Prior to 2005, this MLSI had been in place since at least 1950, and prior to the 1940s it appears that most of Yelverton Bay was occupied by an ice shelf. Analysis of satellite imagery and aerial photographs by White et al. (2015a) indicates that these MLSI losses were associated with the presence of open water adjacent to the Petersen Ice Shelf. At the same time as the MLSI losses, the Petersen Ice Shelf incurred losses of 8.0 km^2 (16%) in August 2005 and 9.0 km^2 in August 2008. Further open water conditions in Yelverton Bay in summer 2011 (Fig. 10.1b) and summer 2012 were also closely related to losses from the Petersen Ice Shelf in these years (Table 10.1). The 'Wootton Peninsula Ice Shelf' (unofficial name), on the west side of Yelverton Bay (Fig. 10.1), also lost 65.6% of its area between 2005 and 2009, with ~8 km^2 lost in August 2005 and ~8.4 km^2 lost in August 2008, during periods of open water adjacent to its terminus (Pope et al. 2012).

To understand broader relationships between the occurrence of open water and the loss of ice shelves, we developed an 'Open Water Index' to quantify the timing and relative extent of open water leads along the coastline of northern Ellesmere Island between 1997 and 2011 (Fig. 10.7). This index was calculated by multiplying the ice areas mapped in weekly Canadian Ice Service charts by the fraction of open water (in tenths) in each polygon that was considered to be a lead (<7/10 ice concentration) (Richer McCallum et al. 2014). The presence of leads was confirmed against MODIS satellite images, which were also used to more accurately define the start and end dates of open water events than was possible with the weekly ice charts. When the timing of ice shelf calving events is compared to the open water

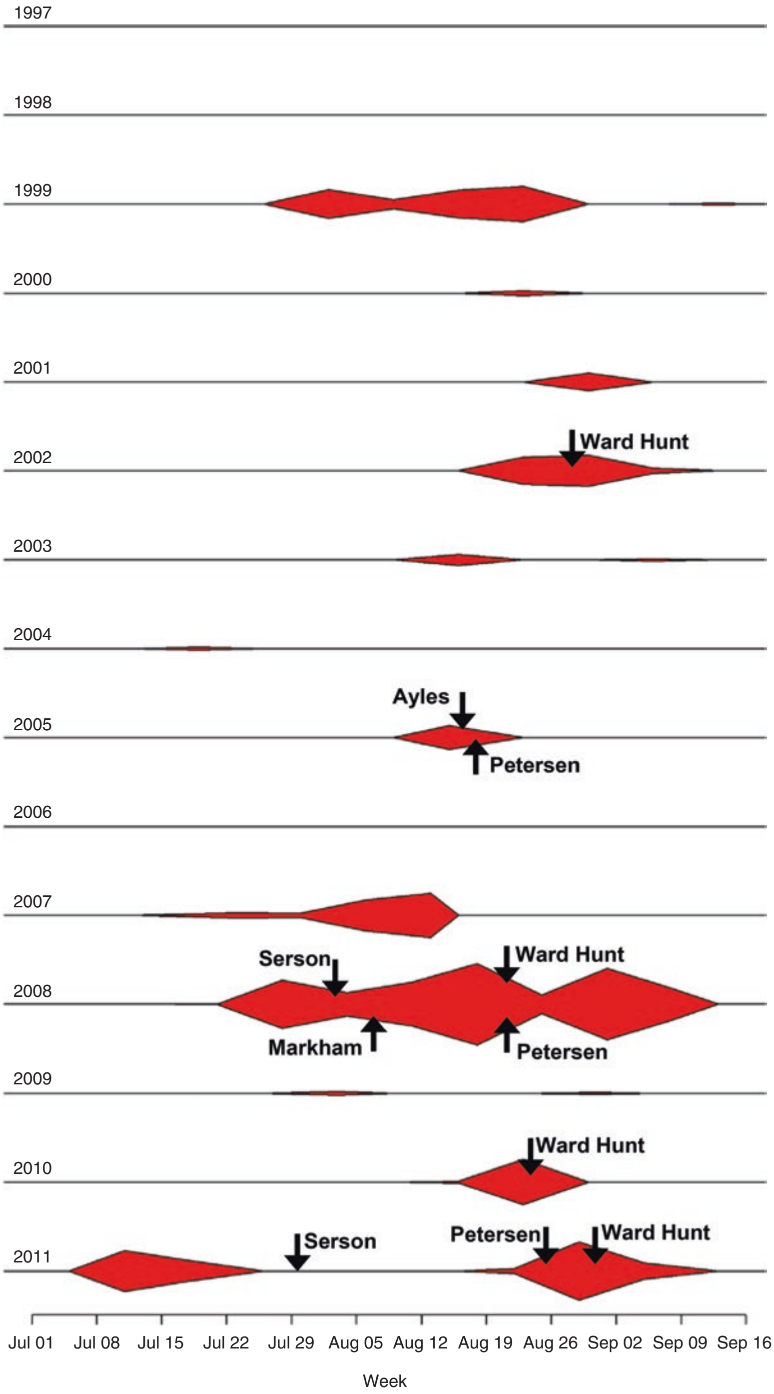

Fig. 10.7 Duration and relative size of open water events (*red shading*) along northern Ellesmere Island, 1997–2011, derived from an Open Water Index calculated from the Canadian Ice Service Digital Archive. In terms of area, the largest recorded event on August 18, 2008, had an Open Water Index of 8980 km^2. *Arrows* indicate the approximate date of major ice shelf calving events (see Table 10.1 for details)

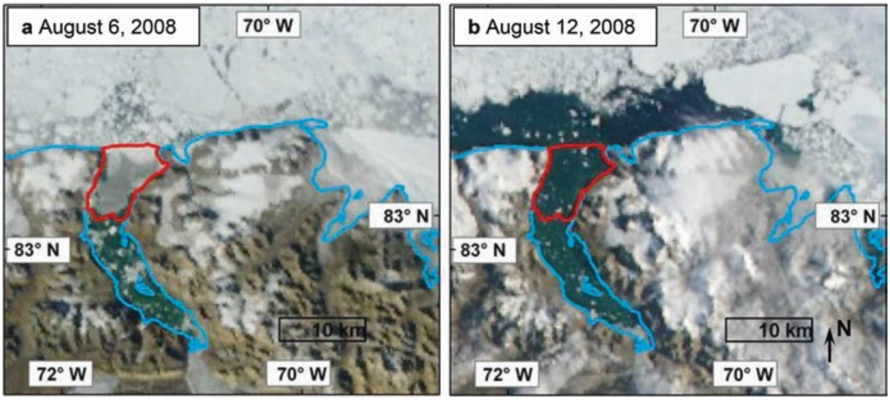

Fig. 10.8 MODIS satellite imagery showing the loss of the Markham Ice Shelf (outlined in *red*) during an open water event between: (**a**) August 6, 2008, and (**b**) August 12, 2008 (MODIS base imagery courtesy of the Rapid Response Project at NASA/GSFC)

index, it is clear that there is a strong relationship between the two (Fig. 10.7). Years with large and long-lived open water conditions along northern Ellesmere Island correspond to periods of extensive ice shelf calving events (e.g., in 2008), but there are few to no ice shelf losses in intervening years with little open water (e.g., 2006, 2009). For example, the entire Markham Ice Shelf was lost during an open water event in early August 2008 (Fig. 10.8), likely making this fiord ice-free for the first time in at least 3500 years (England et al. 2017). Similarly, 60% (122 km^2) of the Serson Ice Shelf calved away during a period of open water in late July 2008, with a further 45 km^2 of the ice shelf lost shortly after another open water event in early August 2011 (Fig. 10.7; Table 10.1).

10.6 Epishelf Lake Ice Changes

Most of the ice shelf calving events described above have occurred in relation to open water conditions at their seaward (outer) edge, such as the loss of the Ayles, Markham and Serson ice shelves. However, there are also several recent examples where open water conditions have existed in the fiords at the rear of ice shelves, resulting in the loss of extensive ice shelf areas from their landward margins. Unlike Antarctic ice shelves, which are typically fed by glaciers along their inner margin, many Arctic ice shelves have been historically bordered along their landward margins by perennially ice-covered epishelf lakes (Veillette et al. 2008, 2011; Jungblut et al. 2017). These epishelf lakes contain freshwater, which typically originates from snow and ice melt and runoff from the surrounding drainage basin (Hamilton 2016). This relatively buoyant freshwater forms a permanently stratified layer which overlies marine water below, and becomes trapped at the rear of the ice shelf. Veillette et al. (2008) suggested that a total of nine epishelf lakes were present along

Fig. 10.9 View of Disraeli Fiord and the rear of the Ward Hunt Ice Shelf, August 20, 2008. Note the extensive calving from the ice shelf into the area previously occupied by an epishelf lake (which drained in 2000–2002) (Photo used with permission of Denis Sarrazin, Université Laval)

northern Ellesmere Island in 1960. This number has been reducing over the past decade due to events such as the fracturing of the Ward Hunt Ice Shelf between 2000 and 2002, which resulted in the loss of the epishelf lake in adjacent Disraeli Fiord (Mueller et al. 2003). The freshwater layer in this epishelf lake was previously up to 43 m thick in the 1960s, 30 m thick in the 1980s and 28 m thick in 1999, with its thinning reflecting a reduction in the minimum draft of the Ward Hunt Ice Shelf over time. After the epishelf lake had drained from Disraeli Fiord it was replaced by seawater, which has been seasonally ice-free for many summers in the recent past. This has allowed extensive fracturing and iceberg calving to occur from the rear of the Ward Hunt Ice Shelf, such as that observed in summer 2008 (Fig. 10.9). Similarly, the majority of the Petersen Bay epishelf lake drained in August 2005, in close relation to the fracturing and calving of the Petersen Ice Shelf (White et al. 2015b). The epishelf lake partly reformed during 2005 and 2008, but there is little evidence that it has been present since 2009 when open water conditions have occurred at the rear of the ice shelf each summer. White et al. (2015a) provided evidence that substantial fracturing and calving from the rear of the Petersen Ice Shelf has also occurred during these times.

10.7 Other Factors: Tides and Seismic Activity

Past studies have suggested that other factors may also be important in the losses of Arctic ice shelves. For example, Holdsworth (1971) reported on the calving of the entire outer portion of the Ward Hunt Ice Shelf between August 1961 and April 1962, which reduced the ice shelf area at that time by almost half (Hattersley-Smith 1963). He argued that this calving event likely occurred in February/March 1962 during a period of abnormally high tides and shortly after a magnitude 3.4 earthquake that occurred ~50 km from the west end of the ice shelf. However, no direct observations were made of this calving event, so the timing of losses is ambiguous and it is difficult to envisage how calving could have occurred in midwinter when there is usually thick sea ice pushed up against the ice shelves. In a later study, Copland et al. (2007) found no evidence for a connection between tidal activity and the well-defined calving of the Ayles Ice Shelf on August 13, 2005. Northern Ellesmere Island has an unusually low tidal range, typically <0.20 m between high and low tides (http://www.tides.gc.ca), so tidal currents are likely relatively weak there. There is also no other evidence for a connection between seismic activity and the losses of an Arctic Ice Shelf, and it is questionable as to how much influence a relatively small (magnitude 3.4) earthquake would have on an ice shelf when any resultant waves would have been dampened by the extensive sea ice cover typically present in the winter. That is not to say that earthquakes are entirely insignificant for ice shelf calving events, as Brunt et al. (2011) reported on the importance of the 2011 Japanese Honshu earthquake and tsunami in causing calving from the Sulzberger Ice Shelf, Antarctica, >13,000 km away from the earthquake epicentre. However, this earthquake and tsunami were one of the largest in recorded history, and the Sulzberger ice shelf faces the open Southern Ocean, so does not provide a good analogue for the enclosed ocean conditions present on northern Ellesmere Island.

10.8 Discussion and Conclusions

It is evident that the Ellesmere Island ice shelves have been undergoing dramatic losses in the recent past. Long-term losses appear to be related to long-term changes in surface air temperature, with rapid warming in the 1940s–1960s (mainly in the summer) and in the 2000s (mainly in the winter) corresponding to periods of rapid ice shelf losses. There is also evidence that the Arctic Ocean has warmed recently, particularly in the 1990s (Gerdes et al. 2003) and the mid-2000s (Polyakov et al. 2010; Beszczynska-Möller et al. 2012). This long term warming has caused ice shelf thinning, both in terms of their in situ surface and basal mass balances, as well as in terms of reductions in mass inputs from tributary glaciers (e.g., Ayles, Milne and Petersen ice shelves; Figs. 10.3, 10.4, and 10.5). While these long term changes likely caused ice shelf weakening, they do not define the exact timing of major ice shelf calving events.

Frequent satellite observations of Arctic ice shelves over the past decade indicates that the precise timing of an ice shelf calving event is closely related to the presence of adjacent open water at the front and/or rear of the ice shelf (Fig. 10.7). Satellite imagery indicates that the presence of sea ice (particularly MLSI) plays a crucial control in stabilizing ice shelves, with few ice shelf calving events occurring when adjacent sea ice and/or epishelf lake ice is present. In the twentieth century the coastline of northern Ellesmere Island was typically fringed by a border of semi-permanent MLSI that remained in place for years to decades. However, this MLSI has been almost entirely lost since the start of the twenty-first century, removing the protection at the front of the ice shelves. There has been some debate as to exactly which physical effect causes an ice shelf to calve when exposed to open water, but suggestions have included increased exposure to wave action (Copland et al. 2007), offshore winds (Ahlnès and Sackinger 1988; Copland et al. 2007), changes in pack ice pressure and buttressing (Koenig et al. 1952), and collisions with mobile sea ice fragments. Further field measurements, remote sensing and modeling are needed to resolve the relative importance and interactions of these factors. There is little evidence to support the occurrence of earthquakes as a factor in the calving of Arctic ice shelves, while the role of tides is equivocal.

The mechanism of losses for Arctic ice shelves has been quite different from Antarctic ice shelves, particularly those on the Antarctic Peninsula. In particular, the unique ability for some Arctic ice shelves to calve from both their seaward and landward margins into the ocean and their own fiords, respectively, has likely accelerated their recent decline, particularly for the Ward Hunt and Petersen ice shelves since 2005. There are no known examples of Antarctic ice shelves that have calved from their landward margin into their own fiords as almost all Antarctic ice shelves are supplied by significant glacier inputs. The style of calving has also been quite different, with the Larsen A and B ice shelves on the Antarctic Peninsula disintegrating into thousands of parallel pieces due to an ‘ice-shelf-fragment-capsize’ mechanism driven by the penetration of water into surface crevasses (MacAyeal et al. 2003). The relative lack of glacier inputs to Arctic ice shelves means that crevasses on them are rare, and several of them have broken away as large single pieces in recent years (e.g., Ayles Ice Shelf: Copland et al. 2007; Markham Ice Shelf: Mueller et al. 2008). On the Antarctic Peninsula there have been dramatic increases in glacier motion and ice discharge in response to losses of adjacent ice shelves (De Angelis and Skvarca 2003; Berthier et al. 2012). However, the relative lack of glacier inputs to Arctic ice shelves, and the fact that these inputs are declining over time, also means that there has been little evidence of glacier changes in response to ice shelf losses on Ellesmere Island.

In conclusion, the outlook for survival of the remaining Ellesmere Island ice shelves is poor. There is no evidence for recent ice shelf regeneration, with current mass balances strongly negative due to surface melting, basal melting and reductions in inputs from tributary glaciers. Rapid reductions in Arctic ice shelf extent, age and thickness, and particularly losses of MLSI from the coastline of northern

Ellesmere Island, together with losses of epishelf lakes and their once permanent ice cover, have exposed the ice shelves to increasing periods of open water around their margins. This has led to ice shelf calving, which is likely to continue under current climate conditions and continuing reductions in Arctic sea ice.

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