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# Rapid loss of the Ayles Ice Shelf, Ellesmere Island, Canada

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[1] On August 13, 2005, almost the entire Ayles Ice Shelf (87.1 km$^2$) calved off within an hour and created a new 66.4 km$^2$ ice island in the Arctic Ocean. This loss of one of the six remaining Ellesmere Island ice shelves reduced their overall area by ~7.5%. The ice shelf was likely weakened prior to calving by a long-term negative mass balance related to an increase in mean annual temperatures over the past 50+ years. The weakened ice shelf then calved during the warmest summer on record in a period of high winds, record low sea ice conditions and the loss of a semi-permanent landfast sea ice fringe. Climate reanalysis suggests that a threshold of >200 positive degree days year$^{-1}$ is important in determining when ice shelf calving events occur on N. Ellesmere Island. **Citation:** Copland, L., D. R. Mueller, and L. Weir (2007), Rapid loss of the Ayles Ice Shelf, Ellesmere Island, Canada, *Geophys. Res. Lett.*, *34*, L21501, doi:10.1029/2007GL031809.

## 1. Introduction

[2] The northern coast of Ellesmere Island contains the last remaining ice shelves in Canada, with an estimated area of 1043 km$^2$ [*Mueller et al.*, 2006]. These ice shelves began to form around 4500 years ago [*Evans and England*, 1992], with reports from early explorers suggesting that they were extensive along the entire coast of N. Ellesmere Island in the late 1800s and early 1900s [*Jeffries*, 2002]. Over the period 1906–82, there has been a 90% reduction in the areal extent of ice shelves along the entire coastline [*Vincent et al.*, 2001], leaving 6 major ones in 2004 [*Mueller et al.*, 2006].

[3] Most ice shelf disintegration took place before the 1950s [*Koenig et al.*, 1952], with some large calving events also occurring up to the 1960s [*Hattersley-Smith*, 1967; *Hattersley-Smith*, 1963]. For example, approximately 596 km$^2$ of the Ward Hunt Ice Shelf (WHIS) calved in the early 1960s [*Hattersley-Smith*, 1963]. Relatively minor changes have occurred since then [*Jeffries and Serson*, 1983; *Mueller et al.*, 2003] (excluding the present study). Up to 40 km$^2$ of the WHIS was lost between spring 1980 and 1982, and ~40 km$^2$ was lost in 1982–83 (including 'Hobson's Choice' ice island) [*Jeffries and Serson*, 1983]. After this period, ~6 km$^2$ of the WHIS and ~20 km$^2$ of associated multiyear landfast sea ice (MLSI) were lost in 2002, although no ice islands of appreciable size formed at this time [*Mueller et al.*, 2003]. All of these losses have been essentially permanent, as there is little to no evidence of recent ice shelf regrowth after calving.

[4] This paper focuses on the rapid loss of almost all of the Ayles Ice Shelf on August 13, 2005, and associated events involving the calving of the Petersen Ice Shelf and loss of semi-permanent MLSI along N. Ellesmere Island. We document and explain these phenomena using a series of satellite images, seismic records, buoy drift tracks, weather records, climate reanalysis and tide models. All times quoted here have been standardized to Coordinated Universal Time (UTC).

## 2. Study Site and Historical Background

[5] The Ayles Ice Shelf occupied the outer portion of Ayles Fiord (82°45′N, 80°00′W; Figure 1), and originated mainly from in situ surface accumulation and basal accretion of ice [*Jeffries*, 1992; *Mueller et al.*, 2006], together with the inflow of glacier ice from upstream (Figure 2a). The ice shelf calved 15 km$^2$ from its northern edge and shifted to the northwest by up to 4 km from its original position between 1962 and 1966 [*Hattersley-Smith*, 1967; *Jeffries*, 1986]. A MLSI 're-entrant' (re-entrants are areas where recently calved ice shelf has been replaced by MLSI) filled the ~17 km$^2$ area between the northeast corner of Ayles Fiord and the displaced ice shelf [*Jeffries*, 1986], growing to a thickness of 2.1 m in 1982 [*Jeffries*, 1982] and 7 m by 1985 [*Jeffries*, 1987]. Examination of a 1984 air photo mosaic (not shown) and a 2002 ASTER image (Figure 2b) showed that 20 km$^2$ of ice from the southern calving front of the ice shelf and 12 km$^2$ of floating glacier ice was lost during or following the mid-1960s event, which was previously unrecognized by *Jeffries* [1986] and *Mueller et al.* [2006].

[6] MLSI commonly fringes the coastline and the ice shelves of N. Ellesmere Island (Figure 1b). It is relatively stable in embayments, but its extent is more temporally variable along headlands where it is exposed to moving pack ice. Yelverton Bay, which was the calving site of ice islands T1, T2 and T3 between 1935 and 1946 [*Jeffries*, 1987], has been occupied by MLSI since T3 calved [*Jeffries*, 1992]. In early 2005 this re-growing MLSI was 59 to 70 years-old and was fringed with a band of younger (12 to 17 years) MLSI extending between Milne Ice Shelf and the headland west of Yelverton Bay. This recent MLSI fringe includes the 'Milne re-entrant', a 4 × 7 km section of MLSI that last broke off in February 1988 [*Jeffries and Sackinger*, 1990].

## 3. Characteristics of the Calving Event

[7] A number of RADARSAT scenes (Table S1 of the auxiliary material)[1] showed that the Ayles Ice Shelf was

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[1]Auxiliary material data sets are available at ftp://ftp.agu.org/apend/gl/2007gl031809. Other auxiliary material files are in the HTML.

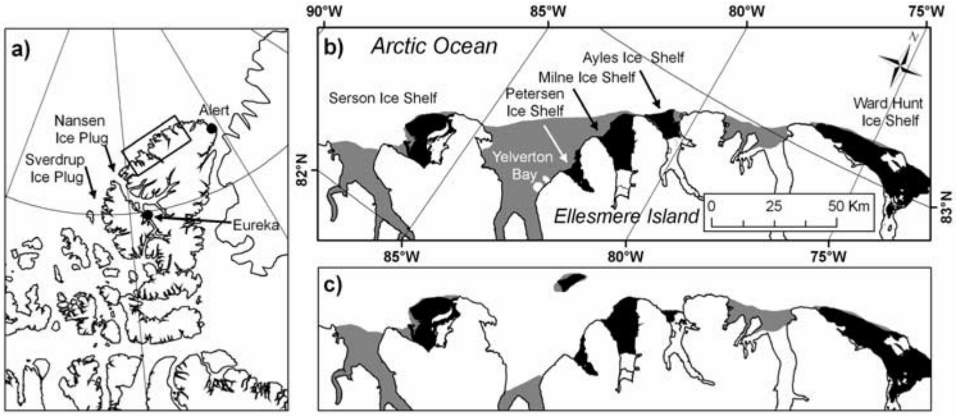


**Figure 1.** (a) Location of the study area (in black box), Nunavut, Canada. (b) Extent of the Ellesmere Island ice shelves (black) and multiyear landfast sea ice (MLSI) (gray) prior to August 2005. (c) Extent of ice shelves and MLSI in late September 2005; note the position of the 'Ayles Ice Island' to the northwest of Milne Fiord.

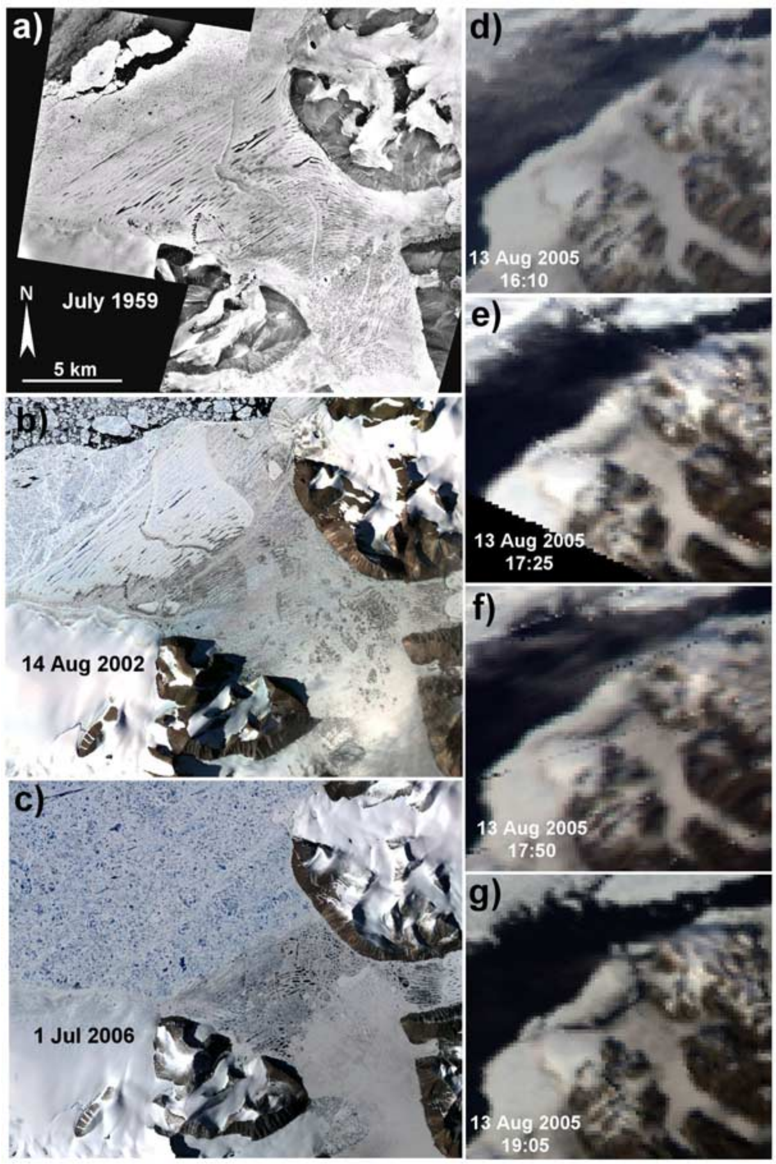


**Figure 2.** Time series of the Ayles Ice Shelf (see Table S1 for source information). (a) Aerial photography July/August 1959 (© Her Majesty the Queen in Right of Canada). (b, c) ASTER images before and after the breakup, respectively. (d, e, f, g) MODIS images during the breakup.

stable during June and July 2005, with sea ice pushed up against a MLSI fringe along its northern edge. Open water conditions were first observed off the northern coast of Ellesmere Island on July 31, 2005, although a ~2 km wide swath of MLSI was still present between the open water and the ice shelf edge. Over the following two weeks the open water increased to a width of ~10 km as MLSI broke away from the front of both Ayles and Milne Ice Shelves.

[8] MODIS scenes from August 13, 2005, show that the width of the open water had reached 15 km, and that the ice shelf was stable in imagery from 14:30, 15:50 and 16:10 (Figure 2d). By 17:25, however, a fracture had developed along a pre-existing crack across the back of the ice shelf, ~6 km from the ice shelf front (Figure 2e). By 17:50 an open water lead was visible between the new 'Ayles Ice Island' and the remnant ice shelf (Figure 2f). At 19:05 the 'Ayles Ice Island' was completely separated from the old ice shelf by up to 1.5 km, with approximately 6 other smaller pieces also breaking off (Figure 2g). The main ice island had a total area of 66.4 km$^2$, with a maximum length of ~15 km and maximum width of ~6 km. The other pieces were up to 4 km long, and totaled 20.7 km$^2$ in area. The Ayles Ice Shelf was almost completely lost in this event, with only sea ice and a few ice blocks now remaining in Ayles Fiord (Figure 2c). Ground-penetrating radar measurements on the Ayles Ice Island in May 2007 indicated that it was 42–45 m thick.

[9] Further MODIS images indicate that the ice island had moved by up to 5 km from its calving location by 00:00 on August 14, to produce a maximum separation rate of >1 km hr$^{-1}$. In the days following the calving event, the smaller ice shelf pieces rapidly dispersed, while the main fragment remained intact and continued to move westwards. By 20:36 on August 18 it was 63.5 km$^2$ in area and ~70 km to the west of where it broke off. By September 24 it had moved ~32 km eastwards back towards Ayles Fiord (centered at 82°43′37″N, 83°29′48″W), and was 57.6 km$^2$ in area. Subsequent RADARSAT scenes indicate that it became lodged in sea ice in this position and moved little until early 2007.

[10] Data from a broadband Strekeisen Model STS-1 seismometer at Alert (260 km east of Ayles Fiord) were obtained from the Global Seismographic Network for the main calving period on August 13, 2005. The main feature of this record is the presence of a strong, low frequency seismic signal in the 2–4 Hz range between 17:15 and 18:30 (Figure S1 of the auxiliary material). It is suggested that this was produced by the calving of the Ayles Ice Shelf as it fractured into the main ice island and smaller fragments. Previous studies at Columbia Glacier, Alaska and the Ross Ice Shelf, Antarctica, have indicated similar long-duration, low frequency seismic signals in relation to large calving events [*Qamar*, 1988; D. MacAyeal, personal communication, 2006].

[11] Prior to the Ayles calving event, RADARSAT imagery from August 6, 2005 (at 19:46) indicates that a total of 330 km$^2$ of MLSI was removed from the outer, more recent portion of Yelverton Bay MLSI, along with the 'Milne re-entrant'. Following the Ayles calving event, RADARSAT imagery from August 18 (at 22:16) recorded the breakup of a further 690 km$^2$ of MLSI in Yelverton Bay that had been in place since at least 1947 (Figure 1c). The terminus of the Petersen Ice Shelf also calved during this period, losing 12.6 km$^2$, or ~20% of its total area (Figure 1c).

## 4. Factors Contributing to the 2005 Ayles Ice Shelf Breakup Event

[12] The surface mass balance of ice shelves without appreciable glacial input is largely determined by climatic variables [*Vaughan and Doake*, 1996]. Since the nearest permanent weather stations are >250 km away from Ayles Fiord (at Eureka and Alert), we used NCEP/NCAR reanalysis of 1000 mb daily air temperatures to provide local data. These indicate that mean annual temperatures at the Ayles Ice Shelf rose at an average rate of +0.37°C decade$^{-1}$ between 1948 and 2006 ($p < 0.0001$; Figure 3a). This mirrors a temperature increase of +0.4°C decade$^{-1}$ for the Arctic (60°–90°N) as a whole between 1966 and 2003 [*McBean et al.*, 2004]. Warming at the Ayles Ice Shelf was particularly strong in the fall ($p < 0.0001$), winter ($p < 0.0001$) and spring ($p = 0.0031$), but there was no significant trend in the summer ($p = 0.4688$) (Figure 3a).

[13] In terms of assessing ice shelf mass balance, a more useful measure than mean monthly temperatures is the calculation of degree days. Positive degree days (PDDs) provide a direct proxy for summer melting, and were typically >200 yr$^{-1}$ between 1948–1963 (Figure 3b), during a period of frequent ice shelf calving along N. Ellesmere Island. Subsequently, cooler summer temperatures prevailed until the early 1990s, during a period with little calving and PDDs rarely exceeding 200 yr$^{-1}$ (with the exception of a brief period in the early 1980s when the WHIS calved). The present period of ice shelf breakup has occurred since PDDs have consistently exceeded 200 yr$^{-1}$, with 2005 having the second highest number of PDDs on record. This was accompanied by an early start to the 2005 melt season, temperatures almost continuously above the long-term (1948–2006) mean, and particularly warm temperatures (2.1°C above average) in the month prior to the Ayles calving event.

[14] Freezing degree days (FDDs) indicate how much an ice shelf is cooled over a given period, and can also provide a useful indicator of ice shelf health [*Vincent et al.*, 2001]. Cooling acts to reduce and/or delay surface warming and melting in the summer, while also offsetting heat inflow to the ice shelf from the ocean. Since 1948 there has been a clear and dramatic reduction in the number of FDDs ($p <$ 0.0000001) (Figure 3b), with 2005 having the lowest on record up to that date (5472 FDDs, compared to the 1948–2006 average of 6370).

[15] Mass balance data from the WHIS [*Braun et al.*, 2004] indicate a long-term negative surface mass balance trend over the past 45 years, with 2002–3 being one of the highest surface ablation years on record (average melt of 0.54 m water equivalent a$^{-1}$). Recent (August 2004–05) mass balance determinations at the *Braun et al.* [2004] stakes found an average loss of 0.38 m w. equation a$^{-1}$, but surface ablation rates 2.5 times higher in sediment-laden areas elsewhere on the WHIS [*Mueller and Vincent*, 2006]. This heterogeneous surface ablation pattern underscores the influence of sediment on ice shelf energy balance and is pertinent to the Ayles Ice Shelf, whose surface had areas of

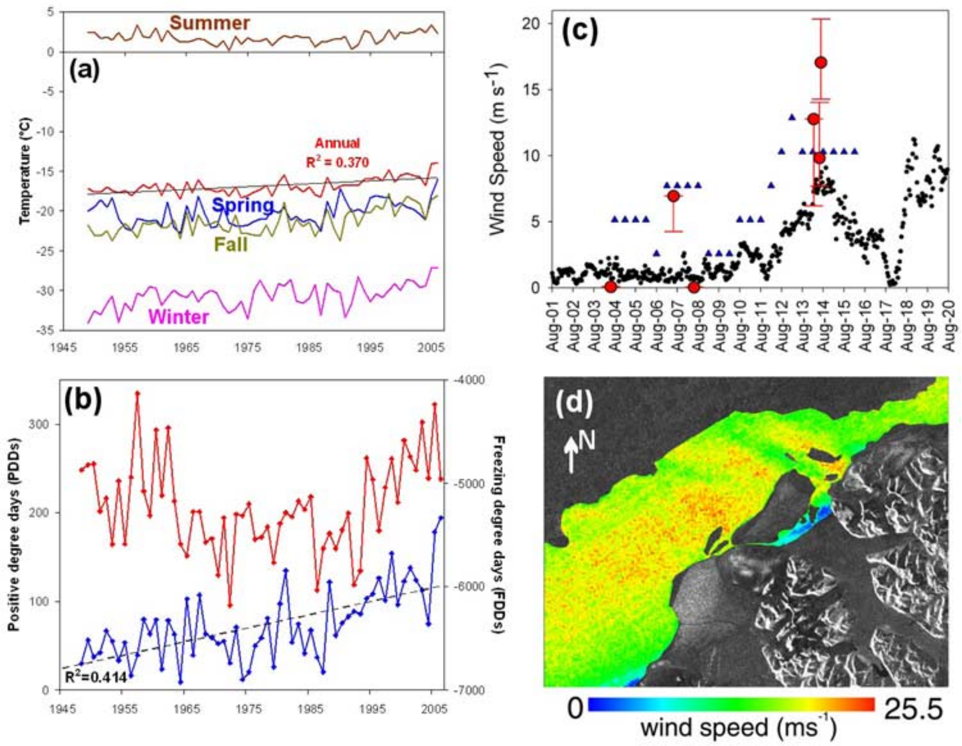


**Figure 3.** (a) Long-term air temperature trends for Ayles Fiord. (b) Number of positive (red, upper line) and freezing (blue, lower line) degree days per year for Ayles Fiord. (c) GEM wind speed reanalysis data for Ayles Fiord (triangles), SAR-derived wind speeds for the open water in front of Ayles Fiord (red circles), and average hourly wind speed measured at Ward Hunt Island (black circles). (d) SAR-derived wind speeds in front of Ayles Fiord on August 13, 2005, at 21:22 ($\sim$3 hours after calving).

sediment-covered ice visible both in 1959 air photos (Figure 2a) and 2002 satellite imagery (Figure 2b).

[16] Over the entire Arctic Ocean, summer 2005 had the lowest sea ice extent up to that date, 21% below the 1979–2000 average, and almost 7% below the previous record low in 2002 [*Serreze et al.*, 2007]. This is also reflected in the significant long-term (1979–2006) trend in minimum (September) sea ice extent of $-8.6 \pm 2.9\%$ decade$^{-1}$ ($p < 0.01$) [*Serreze et al.*, 2007]. It is also noteworthy that the Nansen and Sverdrup ice plugs (Figure 1a) broke up in 2005 [*Alt and Wilson*, 2006]. These semi-permanent MLSI features have only broken up on two previous occasions since 1961 (in 1962 and 1998).

[17] The statistical occurrence of open water conditions in front of the Ayles Ice Shelf was determined by examining 179 ERS-1 and RADARSAT images from January 1992 to July 2005 (Table S2). Open water conditions or evidence of past open water (e.g., young sea ice types) comparable to those observed in August 2005 appeared in 12 (7%) of the images, in 5 of the 13 years analyzed. However, none of these images indicated the complete loss of the MLSI fringe in front of the Ayles Ice Shelf that was observed in August 2005.

[18] Winds appear to have played an important role in the loss of the MLSI fringe as Global Environmental Multiscale (GEM) reanalysis and ground measurements at Ward Hunt Island indicate that N. Ellesmere Island winds were unusually persistent in an offshore to along-shore direction for the first 2 weeks of August 2005. To provide information on local winds at the Ayles Ice Shelf, the open water areas in seven Radarsat scenes from July 31 to August 13, 2005 were analyzed using an inverse version of the CMOD4 algorithm [*Monaldo et al.*, 2001] (Figure 3c). The average hourly wind direction at Ward Hunt Island was used to estimate wind speeds using the normalized radar cross section for each ice-free pixel (as determined from MODIS imagery). In general there was good agreement between the methods, although the GEM reanalysis and SAR-derived winds indicated that speeds were typically higher at the Ayles Ice Shelf than at Ward Hunt Island (Figure 3c). This is particularly true on August 13, when average SAR-derived winds were $\sim$17 m s$^{-1}$ in front of the ice shelf, and locally up to 25 m s$^{-1}$ (90 km h$^{-1}$) (Figure 3d).

[19] Positional data from drifting buoys (International Arctic Buoy Program) near the north coast of Ellesmere Island indicated that sea ice motion (and by inference, ocean currents) was from east to west along the northern coast during July and early-August 2005. The Beaufort Gyre reversed between August 16 and 18, 2005, after the calving event. Therefore, the gyre reversal may have contributed to the eastward motion of 'Ayles Ice Island' a few days after calving, but does not appear to have any causal link with the calving event itself.

[20] Modeled tidal cycles near Ward Hunt Island had a low amplitude (<0.2 m) throughout the period of interest and did not show any particularly high water stages such as spring tides (Fisheries and Oceans Canada; www.tides.gc.ca, last accessed November 2006). Given these characteristics,

tidal effects are not believed to have had a significant effect on the calving of the ice shelf.

## 5. Discussion and Conclusions

[21] Our analysis indicates that the Ayles Ice Shelf has experienced average warming of 0.37°C decade$^{-1}$ since 1948 (Figure 3a), a corresponding decrease in the number of FDDs, and a rapid increase in the number of PDDs since the early 1990s (Figure 3b). Over this period there has also been a reduction in input from the only glacier that used to flow into the ice shelf (Figure 2a vs. Figure 2b). This has likely led to a long-term negative surface mass balance of this ice shelf, similar to what has been recorded at nearby WHIS [*Braun et al.*, 2004].

[22] Given the pre-weakened state of the Ayles Ice Shelf, the very warm summer of 2005 combined with the lowest sea ice extent on record [*Serreze et al.*, 2007] appear to have provided the conditions necessary for its final breakup. In addition, persistent off- and along-shore winds during the first two weeks of August 2005, combined with the westward Beaufort Gyre current, removed the normal confining pressure of the pack ice and MLSI against N. Ellesmere Island. MLSI is considered to be protective as it physically holds ice shelves in place, protects them from wave impacts and associated thermal and mechanical erosion, and prevents direct collisions with the mobile pack ice. Once the MLSI was removed, unusually high winds of up to 25 m s$^{-1}$ helped to provide the final push necessary for the calving to occur (Figure 3d).

[23] Several other studies have found similar relationships between offshore wind events, low sea ice concentrations and calving events. For example, *Ahlnås and Sackinger* [1988] showed that pack ice movements away from N. Ellesmere Island were related to episodes of geostrophic offshore winds >10 m s$^{-1}$. Similarly, *Reeh et al.* [2001] describe how a tidewater glacier in NE Greenland only calved substantially after the breakup of fringing MLSI because the sea ice acted to hold the frontal region together. *Rott et al.* [1996] report that the 1995 collapse of Larsen-A ice shelf occurred during a period of strong offshore winds and high temperatures, and *Massom et al.* [2006] argued that the 2002 Larsen-B collapse occurred under similar conditions.

[24] An analysis of climate data for the Ayles Ice Shelf supports the hypothesis that ice shelves have a limit of thermal viability beyond which they cannot survive [*Morris and Vaughan*, 2003]. Studies on the Antarctic Peninsula indicate that summer air temperatures provide the most important control on ice shelf stability, with their current limit corresponding with the −1.5°C summertime (Dec–Jan–Feb) isotherm [*Scambos et al.*, 2003]. Given the large climatic and glaciological differences between Antarctic and Arctic ice shelves, temperature thresholds may not be directly comparable as current summertime (Jun–Jul–Aug) temperatures are ~2.2°C at Ayles Fiord. However, it seems likely that a northern ice shelf limit of viability is related to PDDs, with calving and breakup events occurring during sustained periods of >200 PDDs year$^{-1}$. The annual number of FDDs may also play an important role as they have decreased significantly over the past 50 years.

[25] While further work is required to elucidate the exact relationships between climate and ice shelf stability in the Arctic, it is clear that the inability of former ice shelves to regenerate (e.g., Yelverton Bay) indicates that their existence is not viable in the current climate regime. With the combined effects of projected atmospheric warming and increasingly lower sea ice concentrations in the Arctic Ocean [*Holland et al.*, 2006], it is likely that collapse of the N. Ellesmere Island ice shelves will continue.

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