Surface mass balance of the Ward Hunt Ice Rise and Ward Hunt Ice Shelf, Ellesmere Island, Nunavut, Canada

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[1] The Ward Hunt Ice Rise and Ward Hunt Ice Shelf, located on Ellesmere Island, Canada, are two of the northernmost land ice masses on the North American continent. Surface mass balance measurements (excluding calving and subice processes) began in 1959 on the ice rise and in 1966 on the ice shelf but were frequently interrupted, most recently between 1986 and 2002. The surface balance of the ice rise and ice shelf follows the temporal pattern seen on other measured High Arctic glaciers. The overall surface mass losses over the last 45 years have been comparatively low (1.68 m water equivalent (w eq) for the ice rise and 3.1 m w eq for the ice shelf), which reflects their proximity to the Arctic Ocean. Nevertheless, the ice shelf appears to have weakened sufficiently in recent years to raise concerns about its possible disintegration in the near future. The 2002/2003 balance year was the most negative year on record (−0.33 m w eq for the ice rise and −0.54 m w eq for the ice shelf). Dynamical stresses related to wind, wave, and tidal action may further accelerate this process, as open water conditions on the Arctic Ocean become more prevalent. The Ward Hunt Ice Rise has so far remained in a reasonably healthy state in terms of its overall surface mass balance, although its long-term survival is also threatened by current and predicted future climatic conditions. *INDEX TERMS:* 1827 Hydrology: Glaciology (1863); 1863 Hydrology: Snow and ice (1827); 9315 Information Related to Geographic Region: Arctic region; *KEYWORDS:* glacier, Arctic

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1. Introduction

[2] The Ward Hunt Ice Rise (WHIR) and Ward Hunt Ice Shelf (WHIS) are two of the northernmost land ice masses on the North American continent (Figures 1 and 2). Scientific studies of the ice shelves and ice rises fringing the northern coast of Ellesmere Island started some 50 years ago [*Hattersley-Smith et al.*, 1955], with detailed surface mass balance measurements beginning in 1959 on the ice rise and 1966 on the ice shelf [*Hattersley-Smith and Serson*, 1970]. Those measurements continued more or less annually until the mid-1970s and more intermittently until the spring of 1989. The University of Massachusetts (UMass) and Parks Canada reinitiated the surface balance measurement program on the WHIR in July 2002. Remarkably, some of the original ablation stakes from the 1959/1966 observation networks had not melted out since they were last surveyed in 1989, and we remeasured those stakes in 2002 and 2003.

[3] Much of the previously collected glaciologic data have been published as governmental or organizational reports [e.g., *Ommanney*, 1977; *Serson*, 1979; *Jeffries*, 1994; *Koerner*, 1996], not readily accessible to the international scientific community. In this paper we present updated surface balance records for the WHIR and WHIS and compare them to other available glacier mass balance data from the Canadian High Arctic. These records are of particular relevance today in light of current public and scientific interest in the Arctic Ocean and its role in the ongoing environmental changes affecting the Arctic region as a whole [e.g., *Serreze et al.*, 2000; *Comiso*, 2003; *Wang and Key*, 2003] and the glaciers of northern Ellesmere Island in particular [e.g., *Vincent et al.*, 2001; *Mueller et al.*, 2003; *Braun et al.*, 2004].

2. Glaciation and Climate of Northern Ellesmere Island

[4] Ice shelves in the Canadian High Arctic are typically formed from in situ accumulations of multiyear landfast sea ice, surface snow accumulations, and basal freezing of seawater, with only minor direct mass input from associated upstream land glaciers (as opposed to the "typical" Antarctic-type ice shelf) [*Hattersley-Smith et

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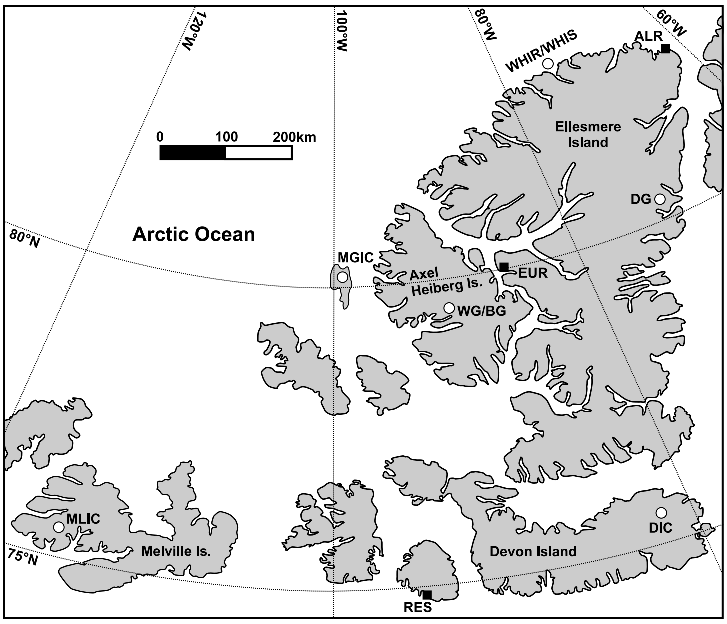

Figure 1. Canadian High Arctic archipelago. Glaciers with long-term mass balance data are indicated by open circles (WHIR/WHIS, Ward Hunt Ice Rise/Ward Hunt Ice Shelf; DG, Drambuie Glacier; MGIC, Meighen Ice Cap; WG/BG, White and Baby Glaciers; DIC, Devon Ice Cap NW; MLIC, Melville South Ice Cap). The operational long-term weather stations (RES, Resolute Bay; EUR, Eureka; ALR, Alert) are indicated with solid squares.

al., 1955; *Vincent et al.*, 2001]. The ice shelves along Ellesmere Island's north coast formed initially some 3000–4000 years ago [*Evans and England*, 1992; *Jeffries*, 1994] as climatic conditions in the High Arctic deteriorated from the early-middle Holocene warm phase [*Bradley*, 1990]. The entire northern coastline of the island appears to have been fringed by a continuous ice shelf ~500 km in length as late as the turn of the century [*Vincent et al.*, 2001]. This large Ellesmere Ice Shelf progressively disintegrated over the course of the twentieth century, and today only ~10% remains [*Vincent et al.*, 2001], the largest remnant being the Ward Hunt Ice Shelf (Figure 2). The ice shelf fractured into two distinct pieces south of Ward Hunt Island between 2000 and 2002, after experiencing some 20 years of relative stability [*Mueller et al.*, 2003]. The causes behind the disintegration of the Ellesmere and Ward Hunt Ice Shelves over the last 100 years are still a subject of debate but are likely a combination of several mechanisms, including wind, wave, and tidal action, pressure by Arctic Ocean pack ice, and recent climate change [*Vincent et al.*, 2001; *Mueller et al.*, 2003]. The Ward Hunt Ice Rise (Figure 2) is between 40 and 100 m thick and formed within the last ~1500 years when the ice shelf thickened and grounded on the isostatically uplifted seafloor north of Ward Hunt Island [*Lyons et al.*, 1972].

[5] The lowest glaciation levels and equilibrium line altitudes (ELAs) in the Northern Hemisphere are found today along the northern coast of Ellesmere Island [*Miller et al.*, 1975], as manifested by coastal ice caps and marine ice shelves (such as the WHIR and WHIS). Frequent fog and low stratus clouds, associated with airflow from the Arctic Ocean, lead to reduced summer ablation in its immediate vicinity [*Paterson*, 1969; *Hattersley-Smith and Serson*, 1970; *Koerner*, 1979]. At the same time, the Arctic Ocean represents a local moisture source [*Bradley and Eischeid*, 1985; *Jeffries and Krouse*, 1987], leading to increased precipitation along the coast relative to the interior parts of Ellesmere Island [*Koerner*, 1979; *Edlund and Alt*, 1989]. However, this "Arctic Ocean effect" is limited to a narrow zone right along the coastline. By contrast, the highest ice margins and ELAs in the Canadian High Arctic (800–1000 m above sea level (asl)) occur on the other side of the British Empire/U.S. Range, on the dry plateau highlands of northeastern Ellesmere Island [*Miller et al.*, 1975; *Koerner*, 1979; *Braun et al.*, 2004].

3. History of the Surface Mass Balance Measurements

[6] Surface balance measurements on the Ward Hunt Ice Shelf began indirectly with R. E. Peary's quest for the North Pole at the turn of the twentieth century [*Peary*, 1907]. During the first scientific exploration of Ellesmere Island's north coast in 1953, G. Hattersley-Smith and colleagues discovered one of Peary's old campsites from 1906 [*Hattersley-Smith et al.*, 1955]. Their finding implies that there was no net accumulation of mass on the ice rise and ice shelf for the first half of the twentieth century [*Hattersley-Smith and Serson*, 1970]. Comprehensive surface balance measurements began in 1959 on the WHIR and in 1966 on the WHIS, with earlier estimates based on limited observations available from 1954 to 1958 [*Sagar*, 1962; *Hattersley-Smith and Serson*, 1970]. The 1959–1968 ice rise and 1966–1968 ice shelf data were published by *Hattersley-Smith and Serson* [1970], and the records up until 1976 were further assessed by *Serson* [1979]. In addition, *Ommanney* [1977] and *Koerner* [1996] compiled parts of

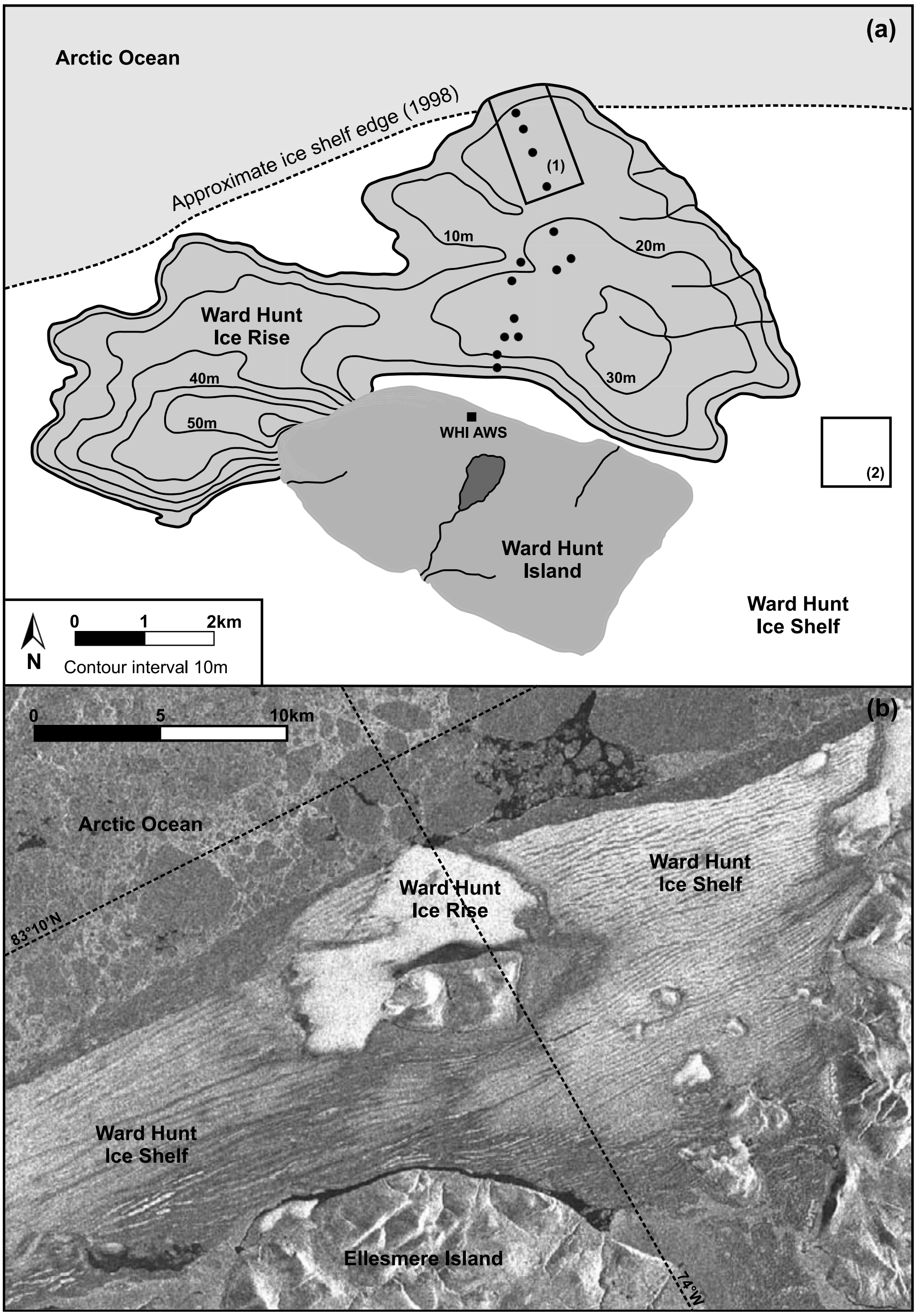

Figure 2. (a) Ward Hunt Ice Rise and surrounding Ward Hunt Ice Shelf. Solid circles mark the ablation stakes installed on the ice rise in 2002. The approximate locations and extents of the original 1959/1966 stake networks on the WHIR (labeled 1) and the WHIS (labeled 2) are indicated by rectangles [*Serson*, 1979]. The Ward Hunt Island weather station (WHI AWS, solid square) is located at ~81°05′N and 74°09′W. (b) RADARSAT 1 image of the Ward Hunt Ice Rise and surrounding Ward Hunt Ice Shelf, 30 August 1998. The ice shelf surface shows the characteristic series of long, parallel ridges and troughs, which form elongated meltwater lakes each summer. Recent calving events have altered the northern margin of the ice shelf [*Mueller et al.*, 2003]. (Modified from *Vincent et al.* [2001, Figure 2], reproduced with their permission.)

both records. The late Harold Serson also meticulously brought together annual summaries of all surface balance measurements on the ice rise and ice shelf up until 25 May 1986 as a comprehensive, handwritten table (dated 1 May 1989). Those data have been discussed by *Jeffries* [1994]. The ablation stake networks were remeasured by R. Fiennes and colleagues on 9 March 1989, allowing H. Serson to calculate the cumulative surface balance of the WHIR and

WHIS between 1986 and 1989 (M. O. Jeffries, personal communication, 2003). In 2002, UMass and Parks Canada personnel installed a new stake transect across the ice rise (Figure 2); remaining usable ablation stakes from the original 1959/1966 networks were measured in 2002 and 2003.

4. Details of the Surface Mass Balance Measurements

[7] The ablation stake networks on the Ward Hunt Ice Rise and Ice Shelf (Figure 2) were designed to measure surface balance changes (excluding calving losses or subice processes) within a relatively restricted area of ~1 km^2 [*Serson*, 1979]. The surface balance records of the WHIR and WHIS therefore do not represent glacier-wide integrated values. Ice rise measurements began in 1959 at 45 ablation stakes [*Sagar*, 1962] that were installed in a grid pattern at the ice rise's northern margin. The interior and higher-elevation areas were not included in the original measurements. On the ice shelf, 100 ablation stakes were installed in 1966 in a 10 × 10 grid pattern (Figure 2), thought to be representative of ~10 km^2 of the larger ice shelf surface [*Ommanney*, 1977]. The number of ablation stakes measured each year decreased over time, as stakes melted out of the ice or were otherwise lost [*Serson*, 1979]. This reduced stake density and coverage, but the accurate number and location of stakes used to determine each yearly value is largely unknown. We consider ±50% as a conservative uncertainty estimate for the presented surface balance data [*Hattersley-Smith and Serson*, 1970]. Field measurements were conducted annually as early as 9 March (1989) and as late as 24 June (1967). Measurements of winter snow accumulation (snow depth and density) thus represent an 8–10 month long window of snow accumulation since the end of the previous summer's ablation season [*Jeffries*, 1994]. The winter balance (b_w) for each site was determined as the average of all available individual stake measurements [*Serson*, 1979]. The average change in ice surface height from the previous year's measurement yielded the summer balance (b_s) for each site. Superimposed ice formation and summer snowfall were not explicitly measured. The annual net surface balance was then calculated as

$$b_n = b_w - b_s.$$

[8] On the ice rise we discovered 19 original ablation stakes in 2002, still in excellent condition, and we were able to compare 16 of them with their last measurement on 9 March 1989. We were unable to find seven stakes measured in 1989, and we assume that they melted out at some point between 1989 and 2002. We did find three additional stakes on the ice rise, which had not been measured in 1989, presumably missed because of darkness and otherwise difficult circumstances in early March. In 2003 we remeasured the original ablation stake network and the stake transect across the WHIR installed in 2002.

[9] On the ice shelf, logistic constraints in 2002 prevented a comprehensive survey of the 1966 stake network, but two original ablation stakes in usable condition were located. We discovered four additional usable stakes during a detailed survey of the ice shelf on 10 August 2003. We were able to match all six recovered stakes with their 1989 measurements, and we assume that the other nine found by Fiennes and colleagues melted out sometime between 1989 and 2003. We averaged ice surface height change values from the 16 ice rise and 6 ice shelf stakes and multiplied the average values by 0.9 [cf. *Hattersley-Smith and Serson*, 1970] to express net surface balance changes in water equivalent (w eq) for 1989–2002 (WHIR) and 1989–2003 (WHIS).

5. Surface Mass Balance of the Ward Hunt Ice Rise and Ice Shelf

[10] Figure 3 presents the surface balance records of the Ward Hunt Ice Rise and Ward Hunt Ice Shelf (1954–2003). The annual surface balance records are continuous, but measurements after 1976 occurred more intermittently (except for several years in the early 1980s), resulting in many multiyear balances. The absence of interannual variability between 1986 and 2002 reflects the aforementioned gap in the observations. Separately measured winter and summer balances are available for about half of all years on record. The 1954–1958 values are estimates based on limited measurements on the ice rise and ice shelf [*Sagar*, 1962; *Hattersley-Smith and Serson*, 1970].

[11] Winter snow accumulation has remained relatively constant from year to year on the ice rise and ice shelf (Figure 3) and compares well with values reported by *Jeffries and Krouse* [1987] for larger-scale snow surveys along the north coast of Ellesmere Island between 1982 and 1985 [*Jeffries*, 1994]. In contrast, summer ablation has been considerably more variable from year to year and largely controls annual surface balance variations. Both records show infrequent positive surface balance years (e.g., 1963–1965 and 1972–1973), but overall negative years dominate [*Jeffries*, 1994]. Summer and annual surface balances have been consistently more negative on the ice shelf compared to those on the ice rise. These differences are consistent with the observations by *Lister* [1962], *Sagar* [1962], *Hattersley-Smith and Serson* [1970], *Serson* [1979], and *Jeffries* [1994] and appear to be related to the characteristic ridge/trough topography [*Koenig et al.*, 1952] and associated formation of elongated meltwater lakes on the ice shelf surface (Figure 2). Ablation within these meltwater lakes is enhanced relative to the ice shelf ridges (or the ice rise) by the continuous presence and flow of liquid water [*Hattersley-Smith*, 1957; *Lister*, 1962].

[12] Annual and summer balances for individually measured years (i.e., excluding those annual values calculated as averages of multiyear balances) are highly correlated between the WHIR and WHIS, whereas the correlation for the respective winter balances is much lower (Table 1). We used this high degree of statistical association to extend the ice shelf record back to 1959 (using a simple linear regression), which allows a better comparison of the respective cumulative surface balances. Since 1959, there has been an overall surface mass loss of 1.68 m w eq on the WHIR (0.04 m w eq/yr) and of 3.1 m w eq on the WHIS (0.07 m w eq/yr) (Figure 3c). Between 1989 and 2002 the ice rise lost 0.44 m w eq of ice (0.03 m w eq/yr), whereas the ice shelf experienced an overall surface mass loss of 1.03 m w eq between 1989 and 2003 (0.07 m w eq/yr). Measurements of two WHIS stakes indicate that ~50% of this mass

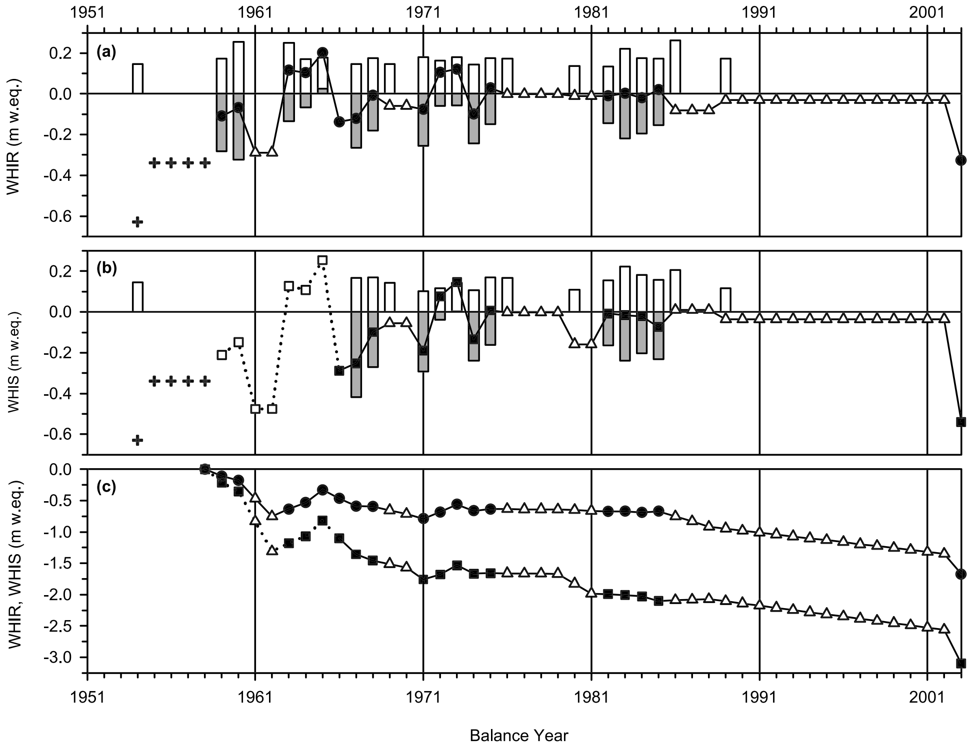

Figure 3. Surface mass balance of the Ward Hunt Ice Rise and Ward Hunt Ice Shelf (1954–2003). (a) WHIR: winter (open bar), summer (shaded bar), and annual (solid circle) surface balance. (b) WHIS: winter (open bar), summer (shaded bar), and annual (solid square) surface balance. (c) WHIR (circle) and WHIS (square) cumulative surface balance (1959–2003). Annual balance values from 1955 to 1958 (crosses) are a multiyear balance estimate based on limited measurements [*Hattersley-Smith and Serson*, 1970]. The 1954 winter and annual balance estimates are from *Sagar* [1962] and *Hattersley-Smith and Serson* [1970]. Annual values calculated as averages of multiyear balances are indicated by open triangles. The 1959–1965 values for the WHIS (open squares and dotted line) are calculated using a linear regression.

(0.54 m w eq) was lost during the 2003 balance year. The year 2003 was also the most negative individually measured year on record for the WHIR, with an annual surface mass loss of 0.33 m w eq. Measurements along the new stake transect showed that the WHIR was entirely in the ablation zone in 2003. Ice surface lowering was greatest (60–70 cm) at lower elevations near the ice margin (i.e., area of original stake network) and much less (~20 cm) at higher-elevation stakes toward the center of the ice rise.

[13] It is important to note that the 1989–2003 surface balance (−1.03 m w eq) of the WHIS is based on measurements at only six ablation stakes. *Lister* [1962], *Sagar* [1962], *Hattersley-Smith and Serson* [1970], and *Serson* [1979] have commented on the high degree of local variability in accumulation and ablation; thus the 1989–2003 ice shelf value needs to be viewed with caution. We consider the 1989–2002 net surface balance of the WHIR (−0.44 m w eq) as more reliable because it represents an average of 16 individual stake measurements. However, the latter parts of both records may progressively underestimate actual surface mass losses, as the total number of stakes contributing to each annual average decreased, with those at (locally) high melt locations (e.g., stakes inside ice shelf meltwater lakes) likely to have been lost earlier. One must also keep in mind that these records represent a relatively

Table 1. Summary of Surface Mass Balance Measurements (1959–2003) on the Ward Hunt Ice Rise and Ward Hunt Ice Shelf[a]

	WHIR	WHIS
Winter Balance		
Mean snow depth, m	0.52 (0.48)	0.50
Mean snow bulk density	0.35 (0.36)	0.31
Mean snow accumulation, m w eq	0.18 (0.17)	0.15
Number of years measured	21	16
Coefficient of determination R^2, 16 years	0.41 (p = 0.008)	
Summer Balance		
Mean ablation, m w eq	−0.17 (−0.18)	−0.20
Number of years measured	16	11
Coefficient of determination R^2, 11 years	0.84 ($p < 0.0001$)	
Annual Balance		
Mean annual balance, m w eq	−0.04	−0.07
Cumulative annual balance, m w eq	−1.68	−3.1
Number of years measured	45	45
Coefficient of determination R^2, 12 years[b]	0.89 ($p < 0.0001$)	

[a]Ward Hunt Ice Shelf (WHIS) measurements began in 1966. The 1959–1965 values were estimated from Ward Hunt Ice Rise (WHIR) measurements. Values in parentheses refer to years with measurements at both sites.
[b]Only individually measured years are used (i.e., excluding annual values based on averages of multiyear surface balances).

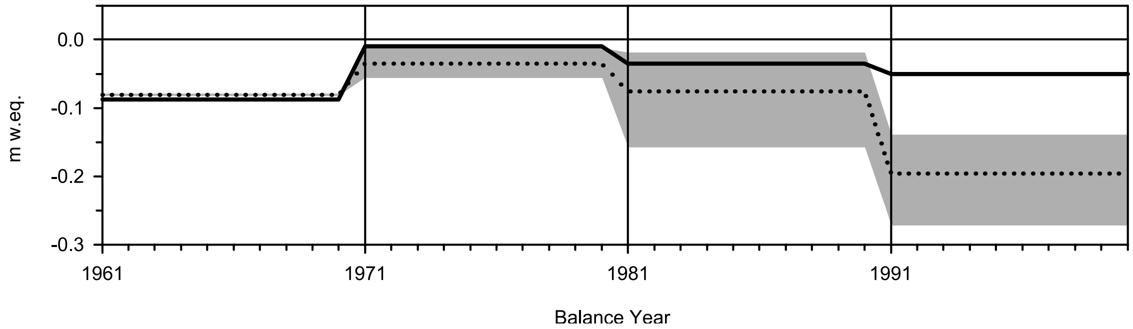

Figure 4. Decadal mass balance means for selected Canadian High Arctic glaciers (1961–2000). Shaded region indicates the composite range in decadal values for the White Glacier, Devon Ice Cap, and Meighen Ice Cap, with the decadal mean for this group of glaciers indicated by a dotted line. The decadal mean combined surface mass balance for the WHIR and WHIS is shown by a solid line.

small area at both sites (Figure 2). In addition, the ice shelf stakes are only useful to gauge mass changes at the ice shelf's upper surface, providing no information about mass gains or losses occurring at the bottom of the floating ice shelf through melting and accretion of seawater [cf. *Hattersley-Smith and Serson*, 1970]. Past ice thickness estimates for the WHIS range between 40 and 60 m [*Crary*, 1958; *Jeffries and Krouse*, 1984; *Jeffries*, 1994], although *Mueller et al.* [2003] have shown evidence for a substantial thinning of the ice shelf (down to ~25 m) since 1980, at least in one area south of Ward Hunt Island.

6. Comparisons With Other High Arctic Glaciers

[14] The mass balance of all monitored glaciers in the Canadian High Arctic has been predominantly negative over the last four decades [*Koerner*, 1996; *Dowdeswell et al.*, 1997; *Serreze et al.*, 2000], with a consistent turn toward increasingly negative values during the 1990s (Figure 4 and Table 2). The surface balances of the WHIR and WHIS track this general temporal pattern, but the magnitude of their surface mass losses has been comparatively low, especially for the most recent decade (1991–2000). This difference, and more fundamentally, the existence and survival of the WHIR and WHIS, reflects the localized influence of the Arctic Ocean on the prevailing climatic conditions along the northern coast of Ellesmere Island [*Paterson*, 1969; *Koerner*, 1979]. The glacier-wide integrated mass balance of the WHIR has probably been much less negative than the data from the restricted original observation network would suggest, as the ice rise supported an interior accumulation area for much of the last 45 years. Within the original stake network (Figure 2), ablation stakes at lower elevations and closer to the ice margin experienced considerable surface lowering since 1989, whereas the more interior stakes (above ~15 m asl) actually showed net mass gains. The stake evidence is corroborated by the nature of the ice surface observed in 2002 and 2003. Considerable accumulations of wind-blown dust, together with well-developed cryoconite holes, are characteristic at lower elevations near the ice margin, whereas the ice surface toward the center and higher elevations of the ice rise is very clean, white ice.

[15] The closest glaciological analogue to the WHIR and WHIS in the Canadian High Arctic is the Meighen Ice Cap, a low-elevation, coastal ice cap located ~500 km to the southwest on Meighen Island (Figure 1). The existence and survival of this ice cap and its continued survival have also

Table 2. Summary of Glacier Mass Balance Records From the Canadian High Arctic and Decadal Mean July Air Temperature at Ward Hunt Island[a]

Glacier Name	1951–1960 Mean	1961–1970 Mean	1971–1980 Mean	1981–1990 Mean	1991–2000 Mean	1961–2000 Mean/Cumulative
Ward Hunt Ice Rise	−0.310[b]	−0.05	0.01	−0.03	−0.03	−0.03/−1.11
Ward Hunt Ice Shelf	−0.34[b]	−0.12[c]	−0.03	−0.04	−0.04	−0.06/−2.2
Drambuie Glacier[d]	NA	NA	NA	−0.40	−0.51	NA
Melville South Ice Cap[e]	NA	0.01[e]	−0.20	−0.15	−0.38	−0.18/−7.01
Meighen Ice Cap	NA	−0.08	−0.06	−0.02	−0.18	−0.08/−3.35
Devon Ice Cap NW	NA	−0.08	−0.01	−0.05	−0.14	−0.070/−2.82
Baby Glacier[f]	NA	−0.06	−0.01[f]	NA	−0.29	NA
White Glacier	NA	−0.08	−0.03	−0.16	−0.27	−0.14/−5.46
July air temperature,[e,g] °C	1.22	1.04	0.80	0.93	0.99	0.94

[a]Decadal mean annual balance values are in m w eq. White/Baby Glacier data are from J. G. Cogley, Glaciology at Trent (available online at http://www.trentu.ca/geography/glaciology.2003/glaciology.htm), and Drambuie Glacier, Melville South Ice Cap, Meighen Ice Cap, and Devon Ice Cap NW data were provided by R. M. Koerner (personal communication, 2003). NA means not available.

[b]Limited measurements began in 1954. Detailed measurements started on the WHIR in 1959. The 1959/1960 WHIS values are estimated from WHIR measurements.

[c]Measurements began in 1966; 1961–1965 values are estimated from WHIR measurements.

[d]Drambuie Glacier measurements began in 1977 ("index" balance only; R. M. Koerner, personal communication, 2003).

[e]Melville South Ice Cap measurements began in 1963.

[f]Baby Glacier measurements were interrupted between 1978 and 1989 [*Adams et al.*, 1998].

[g]Mean July temperature at Ward Hunt Island was reconstructed from Alert instrumental data.

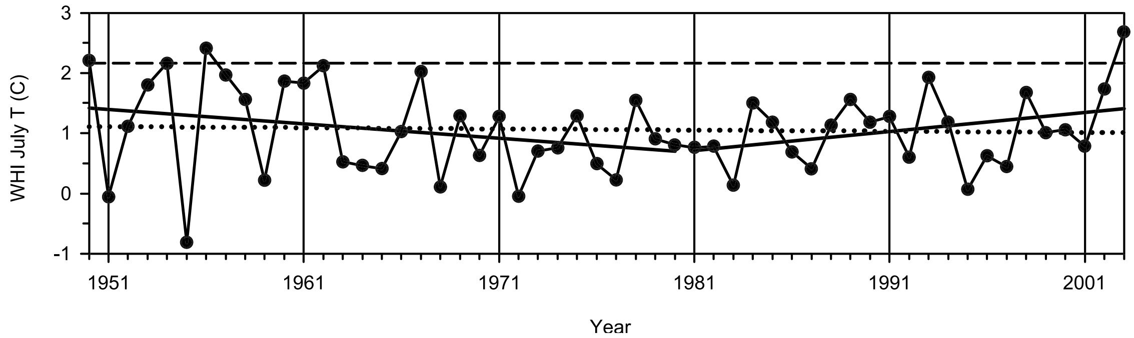

Figure 5. Reconstructed mean July air temperature at Ward Hunt Island (1950–2003), based on a transformation of corresponding Alert monthly temperature. The dotted line indicates the long-term trend between 1950 and 2003 (−0.002°C, p = 0.76). The two solid lines show the 1950–1980 (−0.02°C, p = 0.15) and the 1981–2003 (0.03°C, p = 0.1) trends, corresponding to the "presatellite" and "satellite" era of environmental observations in the Arctic [cf. *Comiso*, 2003]. The mean July air temperature in 1954 at Ward Hunt Island (2.2°C) is indicated by a dashed line.

been explained by locally increased snow accumulation and reduced summer ablation because of its close proximity to the Arctic Ocean [*Paterson*, 1969; *Alt*, 1979; *Koerner*, 1979]. However, the 1990s have been by far the most negative mass balance decade for the Meighen Ice Cap (Table 2) and follow three decades with a weak trend toward less negative mass balance values [*Dowdeswell et al.*, 1997].

7. Surface Mass Balance and Climate Change

[16] Parks Canada has operated an automated weather station on Ward Hunt Island (Figure 2) since June 1995. Mean monthly air temperatures at Alert (Figure 1) and Ward Hunt Island are highly correlated, and we used a third-order polynomial regression to reconstruct a monthly climatology for Ward Hunt Island (R^2 = 0.994; p = 0.09; RMSE = 0.94°C; n = 5 years). July is the only month of the year at Ward Hunt Island with a mean air temperature above freezing (Figure 5), making it a useful index for the surface balance of the ice rise and ice shelf [*Serson*, 1979; *Vaughan and Doake*, 1996]. There is no statistically significant trend in the data over the entire 54 year long record, although there have been increases in local, as well as Arctic-wide, summer temperatures, if one only looks at the last 20–30 years [cf. *Vincent et al.*, 2001; *Mueller et al.*, 2003; *Comiso*, 2003] or at changes since the end of the "Little Ice Age" (LIA) some 100–150 years ago. Decadal mean July air temperature has increased at Ward Hunt Island over the last few decades (Table 2), broadly matching the observed surface balance changes of the WHIR and WHIS (Figure 4) as well as decreases in Arctic Ocean sea ice extent and thickness [*Rothrock et al.*, 1999; *Comiso*, 2002]. However, reduced Arctic Ocean sea ice could actually, at least to some extent, favor more positive surface balances of the WHIR and WHIS by locally increasing accumulation and reducing ablation via an enhanced Arctic Ocean effect [cf. *Hattersley-Smith*, 1960]. Increased summer snowfall may contribute only little additional mass to the ice rise and ice shelf, but it indirectly reduces ablation by raising the albedo of the ice and surrounding land surface [*Hattersley-Smith and Serson*, 1970; *Alt*, 1979]. However, it seems doubtful that such a localized mechanism can sustain the WHIR and WHIS for much longer, as the direct effects of higher summer temperatures (i.e., increased surface melting) should at some point outweigh the localized secondary processes suppressing melt. This situation appears to have been reached on the Meighen Ice Cap farther to the south already during the 1990s (Table 2). It is interesting to note that the four warmest Julys of the last ~35 years (1993, 1998, 2002, and 2003) (Figure 5) all coincided with pronounced minima in Arctic Ocean sea ice cover [*Serreze et al.*, 2003; NASA Goddard Space Flight Center, Recent warming of Arctic may affect worldwide climate, available at http://www.gsfc.nasa.gov/topstory/2003/1023esuice.html].

[17] *Hattersley-Smith et al.* [1955] predicted the disappearance of the WHIS by the year 2035 if summer conditions similar to those of 1954 (mean July air temperature of 5.6°C at Alert and ~2.2°C at Ward Hunt Island) were to become common. Such warm summers had not recurred at Alert over the last ~40 years (Figure 5), until July 2003, which was the warmest July on record at Alert (6.8°C) and Ward Hunt Island (2.9°C). Consequently, the WHIR and WHIS experienced probably their most negative surface balance year (Figure 3). The last several years have also seen considerable physical changes of the WHIS (such as enhanced calving from its northern margin, development of substantial cracks through the ice shelf, and ice shelf thinning) after two decades of relative stability [*Vincent et al.*, 2001; *Mueller et al.*, 2003].

[18] We hypothesize that the gradual mass losses over the last ~100 years may have weakened the ice shelf sufficiently to induce an irreversible disintegration in the near future. It seems likely that dynamic stresses on the ice shelf related to wave, wind, and tidal action have also increased in recent years, as open water conditions on the Arctic Ocean have become more prevalent [cf. *Koenig et al.*, 1952; *Mueller et al.*, 2003]. The refreezing of surface meltwater inside existing ice shelf cracks and fractures may act as an additional positive feedback mechanism [*Scambos et al.*, 2000]. Once the ice shelf has disintegrated, it is unlikely to reform again unless climatic conditions deteriorate dramatically [*Hattersley-Smith et al.*, 1955; *Vaughan and Doake*, 1996].

[19] On the other hand, it is possible that we are witnessing merely an unusual phase of variability, as recorded before in terms of glacier mass balance during the comparatively warm 1950s and early 1960s. Those conditions, however, did not persist, and in fact, much of the Canadian High Arctic experienced overall colder summers and positive glacier mass balance from the mid-1960s to the mid-1970s [*Bradley and Miller*, 1972; *Alt*, 1987; *Braun et al.*, 2004]. The probability of either interpretation must be assessed against the considerable environmental changes already underway in the Arctic [cf. *Serreze et al.*, 2000; *Comiso*, 2003; *Serreze et al.*, 2003; *Wang and Key*, 2003] and the consistency of climate model predictions for a continued, and perhaps accelerated, warming at high latitudes [e.g., *Houghton et al.*, 2001; *Johannessen et al.*, 2004; *Walsh and Timlin*, 2003] in the foreseeable future. Under such conditions the complete breakup of the WHIS may occur earlier than predicted by G. Hattersley-Smith 50 years ago.

8. Summary and Conclusions

[20] We have compiled all surface mass balance data for the Ward Hunt Ice Rise and Ward Hunt Ice Shelf and updated both records through 2003. The surface balance of the ice rise and ice shelf track the mass balance changes of the other monitored High Arctic glaciers, but their surface mass losses over the last 45 years have been comparatively low. This difference reflects the localized influence of the Arctic Ocean on the climatic conditions along the north coast of Ellesmere Island. Nevertheless, overall ice shelf mass losses (including surface melting, reduction in ice thickness, and calving) since the end of the LIA appear to have reached a critical level in recent years, as evidenced by recent fracturing of the ice shelf [*Mueller et al.*, 2003]. The floating ice shelf is particularly sensitive to short-term climatic variability, as its mass balance is not "buffered" by input from upstream land glaciers. Dynamical stresses related to wind, wave, and tidal action may also promote the breakup of the Ward Hunt Ice Shelf as open water conditions on the Arctic Ocean become more prevalent. If the ice shelf disintegrates, it cannot readily reform unless climatic conditions deteriorate dramatically (hysteresis effect) [cf. *Hattersley-Smith et al.*, 1955]. This could leave the Ward Hunt Ice Rise as one of the last remnants of the once extensive ice shelves along the northern coast of Ellesmere Island. The ice rise has remained in a reasonably healthy state in terms of its overall mass balance for much of the last 45 years, although its long-term survival is also threatened by current and predicted future climatic conditions. A collapse of the WHIS would mean the disappearance of an important physical component of the High Arctic landscape and would lead to the destruction of a unique habitat for microbial-based ecosystems [*Vincent et al.*, 2001].

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