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Anomalous recent growth of part of a large Arctic ice cap: Austfonna, Svalbard

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[1] Observations from repeat-pass airborne laser altimetry, acquired in 1996 and 2002, indicate an anomalous positive ice-surface elevation change for the central accumulation area of the largest ice cap in the Eurasian Arctic; Austfonna, eastern Svalbard. The increase is equivalent to 35% of the long-term annual accumulation rate and coincides with the loss of perennial sea ice in the adjacent Barents Sea, which we conclude is the most likely explanation for the increase. Extrapolation of the observed trends in sea ice decline, over the next 50 years, suggests large perturbations in the mass-balance of other Arctic ice masses may be expected. *INDEX TERMS:* 0933 Exploration Geophysics: Remote sensing; 1827 Hydrology: Glaciology (1863); 1699 Global Change: General or miscellaneous; 9315 Information Related to Geographic Region: Arctic region. **Citation:** Bamber, J., W. Krabill, V. Raper, and J. Dowdeswell (2004), Anomalous recent growth of part of a large Arctic ice cap: Austfonna, Svalbard, *Geophys. Res. Lett.*, *31*, L12402, doi:10.1029/2004GL019667.

1. Introduction

[2] The mass-balance of Svalbard glaciers and ice caps has been calculated, using analysis of regional mass-balance gradients, to be slightly negative at -4.5 km^3 ± 1.0 km^3 a^{-1}, based on data covering approximately the last 40 years [*Hagen et al.*, 2003]. This gives a specific net balance of -0.12 m ± 0.03 m a^{-1} for the archipelago. This is consistent with calculations of the mass-balance of Arctic glaciers and ice caps in general, which have been calculated to have a specific net mass-balance of -0.067 m a^{-1} between 1961 and 1990, contributing about 0.05 mm a^{-1} to global sea-level rise [*Dyurgerov and Meier*, 1997]. It has been suggested that this value is almost 20% of the total produced from glaciers and ice caps outside the great ice sheets. Measurements of ice-surface elevation change over the Greenland Ice Sheet during the 1990s have shown extensive peripheral thinning that has been associated with a combination of increased ablation and ice-dynamic effects [*Abdalati et al.*, 2001]. In addition, there is now a substantial body of evidence indicating a widespread change in climate during the 20th Century in the Arctic [*Serreze et al.*, 2000]. Indeed, during the summer of 2002 a record minimum in Arctic sea-ice extent and a record maximum in melt area over the Greenland Ice Sheet were observed [*Serreze et al.*, 2003].

[3] During the springs of 1996 and 2002, airborne laser-altimeter surveys were flown over a number of glaciers and ice caps in the Svalbard archipelago (Figure 1). A complex pattern of elevation change was observed due to a variety of forcing factors including ice dynamics as well as climate. Here we report on the elevation changes measured on the largest ice cap in the Eurasian Arctic, Austfonna, which lies on the island of Nordaustlandet in northeastern Svalbard (Figure 1). The ice cap covers an area of 8,120 km^2, and contains about 22% of the ice volume of the whole archipelago [*Dowdeswell*, 1986; *Dowdeswell et al.*, 1986].

2. Methods

[4] Ice-surface elevation measurements of very high accuracy were acquired using the Airborne Topographic Mapper 3 (ATM3) [*Krabill et al.*, 2000]. The flight lines over Svalbard are shown in Figure 1. The instrument is a conical-scanning laser-ranging system with a pulse-repetition frequency of 5 kHz and a scan rate of 20 Hz in 2002 and 10 Hz in 1996. This gives an along-track data-point spacing of 3 and 6 m, respectively. Aircraft location was determined by kinematic global positioning system techniques, and aircraft pitch and roll were measured using an inertial navigation system. Ice-surface elevations with RMS accuracies of 10 cm or better were obtained from these campaigns [*Krabill et al.*, 1995], allowing the identification of elevation changes (dh/dt) with a magnitude greater than 2.3 cm a^{-1} over a six-year interval.

3. Observations

[5] Repeat observations of ice-surface elevation using the ATM3 indicated that 15% of the ice cap, Austfonna, covering the central and highest altitude area, increased in elevation by an average of 50 cm a^{-1} between 1996 and 2002 (Figure 2). To the northeast of this region, thickening of about 10 cm a^{-1} was also observed. The maximum growth rate represents, when corrected from snow to water-equivalent values, as much as a 40% increase in accumulation rate [*Pinglot et al.*, 2001] and suggests a major disequilibrium in the mass budget of the ice cap.

[6] Net annual accumulation rates above the equilibrium-line altitude (ELA) on Austfonna have been estimated from ice-core data [*Pinglot et al.*, 2001]. Using these data, mean annual net mass-balance was calculated for two periods: 1963–86 and 1986–97. No significant difference was found between these two periods, which is consistent with ice-core measurements from elsewhere in Svalbard [*Pinglot et al.*, 1999]. Little is known about ablation rates below the ELA on Austfonna and, consequently, mass-balance gradients were extrapolated from observations made in the more westerly island of Spitsbergen to estimate the total net

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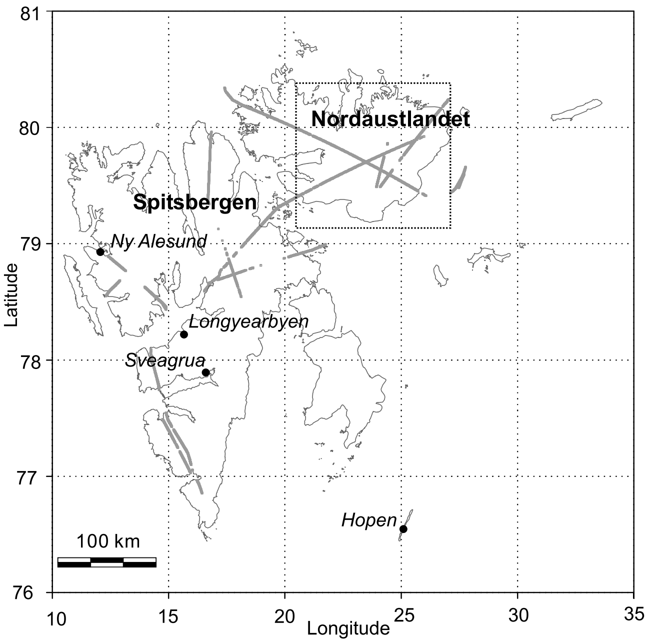

Figure 1. The Svalbard archipelago, showing the flight lines flown during the spring of 1996 and 2002. The three meteorological stations on Spitsbergen and the one in southeastern Svalbard (Hopen) are shown by solid circles.

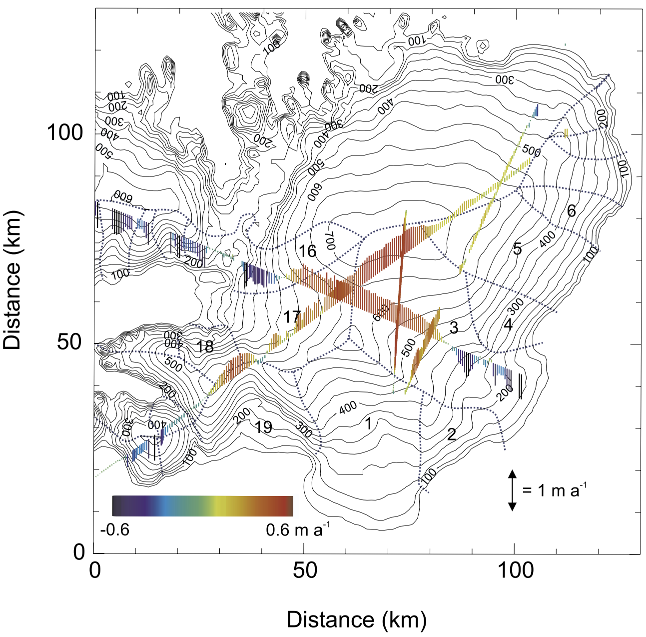

Figure 2. Ice-surface elevation change measurements over the ice cap of Austfonna on the island of Nordaustlandet overlain on a contour plot of surface elevation. Contour intervals are 50 m. The height and colour of the bars indicates the magnitude and sign of the changes. The height of a bar representing a 1 m a^{-1} signal is provided for scale. The location of the plot is shown by the dashed rectangle in Figure 1. Drainage basins (numbered according to *Dowdeswell* [1986]), derived from Landsat MSS imagery are indicated by the dashed blue lines [*Dowdeswell*, 1986].

balance of the ice cap [*Hagen et al.*, 2003]. This approach gave a net mass balance close to zero (i.e., balance). We estimate that the recent increase in accumulation rate inferred from the ATM3 laser-altimeter measurements has increased the net balance of the accumulation area by 26%. Assuming no change in ablation rates over the measurement period, this would shift the ice cap from close to equilibrium to a positive net mass-balance. It is possible, however, that an increase in open water during summer has resulted in increased ablation around the margins, offsetting the accumulation increase. There are, however, insufficient observations to confirm or refute this.

4. Interpretation and Discussion

[7] A number of glaciers in Svalbard are known to be of surge-type [*Hagen et al.*, 1993]. Several drainage basins on Austfonna, of 10^3 km^2 in area, have surged since the 1930s [*Schytt*, 1969; *Dowdeswell et al.*, 1999]. In particular, basins 1 and 17 were believed to have surged in about 1938, and basin 3 around 1870 [*Schytt*, 1969] (basin number are those used by *Dowdeswell* [1986]). It is possible, therefore, that there may be a dynamic component to the dh/dt signal observed (Figures 2 and 3). We discount this as being significant, however, as the largest positive changes in surface elevation are found in the centre of Austfonna, straddling several ice divides (Figure 2), and show no change in pattern or sensitivity with respect to individual drainage basins. In fact, there appears to be no correlation between elevation and dh/dt for the largest positive changes (Figure 3). Only at lower elevations, between about 550 and 350 m a.s.l., does a possible correlation exist. If the elevation change was due to ice thickening after a surge, there should be a significant difference in the pattern of growth between basins 1, 3 and 17. In addition, growth should be inversely proportional to elevation (i.e., highest values at lower elevation and smallest values in the vicinity of the ice divides). Neither of these trends is observed. Furthermore, it has been noted that the basins behave as independent flow units [*Dowdeswell*, 1986; *Dowdeswell et al.*, 1999]. It is difficult, therefore, to identify a mechanism associated with ice dynamics that would produce a maxi-

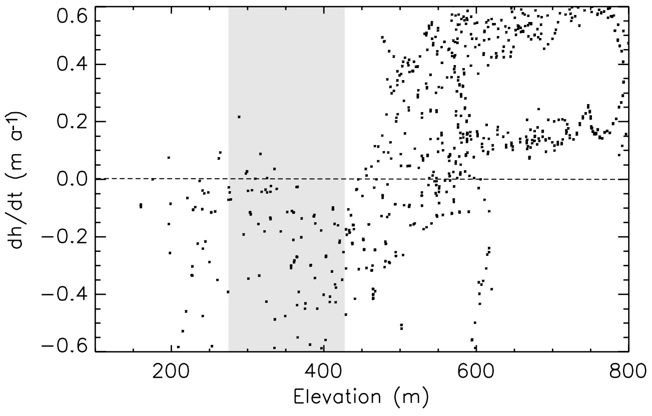

Figure 3. Scatterplot of ice-surface elevation versus surface-elevation change on Austfonna measured by the ATM3 over a six-year period. The approximate equilibrium line altitude is shown by the shaded area on the plot.

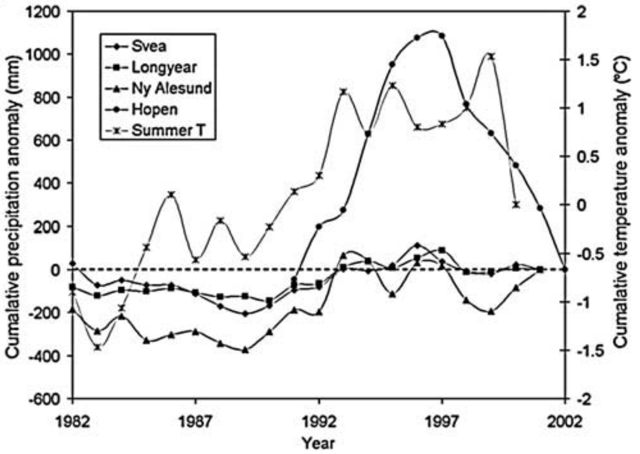

Figure 4. Cumulative anomalies of precipitation and surface air-temperature from the four meteorological stations shown in Figure 1. Anomalies are the deviation of the annual value from the mean over the period of data available. Air temperature data are shown for Ny-Alesund only.

mum elevation increase at, and across, several ice divides. We conclude that the observations do not, therefore, support a hypothesis of dynamically induced thickening as the predominant mechanism for the observed positive elevation change. This suggests that an increase in precipitation over the area is the most probable explanation. The relatively uniform thickening at higher elevations is consistent with this hypothesis.

[8] Meteorological station data from Svalbard were obtained to see if they showed a trend in precipitation that could explain the observations of surface-elevation change on Austfonna. Data for three stations on Spitsbergen and one on a small island in the southeast of the archipelago were obtained from the Norwegian Meteorological Office (Figure 1). The cumulative precipitation anomaly (sum of annual value minus the mean for all years) observed at these stations between 1982 and 2001 is shown in Figure 4 (Hopen has only a twelve-year record). The three sites in Spitsbergen show no statistically significant trend during the interval between ATM flights, whereas the data from Hopen display a substantial decrease since 1997. There is a slight positive trend for the Ny Alesund time series (15.7 mm a^{-1}, with an R^2 of 0.43), but no anomalously high values post, 1996. Spitsbergen, however, is predominantly influenced by weather systems from the west and north-west [*Hagen et al.*, 1993] whereas Nordaustlandet is affected more by weather systems from the east coming off the Barents Sea, as reflected in the observed asymmetric distribution of accumulation across the ice cap which shows a strong decrease away from the south and east [*Pinglot et al.*, 2001].

[9] Thus, the data from the three Spitsbergen stations, which lie approximately 200 km to the west of Austfonna, may not be representative of the climatic conditions over Nordaustlandet. Hopen, although further east, is some 300 km south of Austfonna. Based on the inter-annual variability in precipitation for the three Spitsbergen stations the probability of the six-year trend being random is low, yet there is no obvious corroborating trend in the meteorological station data from Spitsbergen. This suggests that the cause of the increase in ice-surface elevation on Austfonna is likely to be an increase in precipitation that affects part at least of the heavily glaciated eastern islands of Svalbard.

[10] A likely explanation for this increase in precipitation is associated with a reduction in perennial sea-ice cover in the Barents Sea. Modeled (and observed) trends in precipitation in the Arctic have been associated with changes in the sea-ice boundary [*Kattsov and Walsh*, 2000] and it is now well established that Arctic sea-ice extent has been declining since at least 1978 [*Johannessen et al.*, 1999] with, in particular, a 9% per decade decrease in the perennial (summer minimum) sea-ice area and 6.4% decrease in extent since 1978 [*Comiso*, 2002b]. Figure 5 shows the change in perennial sea-ice extent between 1978–1995 and 1996–2002, derived from passive microwave data [*Comiso*, 2002a]. Most striking is the loss of sea ice in the Barents Sea running from the east coast of Spitsbergen almost as far as Novaya Zemlya (Figure 5). Although passive microwave data are problematic for summer conditions, the Bootstrap algorithm is sensitive to thin ice and gives about 20% greater summer sea ice area compared with the other commonly used data set: the NASA team [*Singarayer and Bamber*, 2003]. We assume, therefore, that the Bootstrap algorithm provides a conservative estimate of perennial sea ice reduction. The precipitation data from Hopen (and for a 35 year record from Longyearbyen) indicate a weak seasonality peaking in August–October, supporting the inference that increased open water at this time of year would have a significant impact on the moisture budget. We suggest, therefore, that the satellite-observed reduction in sea-ice cover in this sector of the Arctic has caused an increase in moisture transport across Nordaustlandet from a source to the south and east in the Barents Sea. This has resulted in the anomalous thickening in the central part of the ice cap observed in the laser-altimeter data (Figures 2 and 3). A similar, highly localized, positive elevation change was seen for an ice cap in north-east Greenland, associated with a

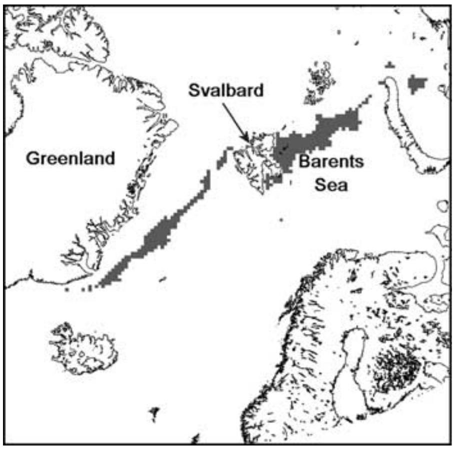

Figure 5. Change in perennial Arctic sea-ice extent (based on the seasonal minimum) between the periods 1978–1995 and 1996–2002 derived from passive microwave data using the 'Bootstrap algorithm' [*Comiso*, 2002a]. The grey shaded areas indicate a change from partial (>20%) to ice-free conditions since 1996.

concomitant appearance of a polynya offshore [*Krabill et al.*, 2000].

[11] We note, in addition, that projections of perennial sea-ice decline for 2050, derived from observations of the trends over the last 30 years, are particularly marked along the north and north-east coastline of Greenland and also in the Canadian Arctic around Ellesmere and Devon islands [*Comiso*, 2002b]. Extrapolation of the observational trends forward in time is strongly corroborated by GCM simulations using two independent models [*Vinnikov et al.*, 1999]. Based on the laser-altimeter observations and environmental interpretations made in this paper, this suggests that the projected changes in Arctic sea-ice cover will have a significant impact on the mass-balance of land ice around the Arctic Basin over at least the next 50 years.

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