Strong surface melting preceded collapse of Antarctic Peninsula ice shelf

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[1] During the austral summer of 2001/02, melting at the surface of Larsen Ice Shelf in the Antarctic Peninsula was three times greater than the average of five previous summers. This exceptional melt event lasted for three months and was followed by the collapse of Larsen B Ice Shelf, during which 3,200 km^2 of ice shelf surface was lost. The strong melting was caused by a persistent atmospheric circulation anomaly, which depleted sea ice concentrations in front of Larsen Ice Shelf and transported warm air to the ice shelf throughout the 2001/02 summer. This supports the theory that large meltwater fluxes accelerate the retreat of Antarctic Peninsula ice shelves. **Citation:** van den Broeke, M. (2005), Strong surface melting preceded collapse of Antarctic Peninsula ice shelf, *Geophys. Res. Lett.*, *32*, L12815, doi:10.1029/2005GL023247.

1. Introduction

[2] Ice shelves, 200–1000 m thick extensions of glaciers, are sensitive to ambient climate. In the Antarctic Peninsula (AP), *Morris and Vaughan* [2003] suggest that the present-day −9°C annual isotherm represents an approximate limit for ice shelf viability. A 2°C warming of the lower AP atmosphere since 1979 has forced this limit southward [*King and Harangozo*, 1998; *Vaughan et al.*, 2003], followed by a gradual retreat of the northernmost AP ice shelves [*Vaughan and Doake*, 1996]. This retreat was punctuated by the catastrophic collapse of the Larsen A ice shelf in January 1995 [*Rott et al.*, 1996, Figure 1]. In February 1998, the front of the more southerly Larsen B ice shelf retreated behind its stable geometrical position [*Doake et al.*, 1998], followed by its catastrophic collapse between 31 January and 7 March 2002, in which event over 3,200 km^2 calved away [*Skvarça and De Angelis*, 2003]. After the break-up, tributary glaciers showed significant acceleration and thinning, indicating increased ice discharge into the ocean [*Rott et al.*, 2002; *De Angelis and Skvarça*, 2003]. Similar interactions between ice-shelves and feeding glaciers may presently be active in the Amundsen Sea coast of West Antarctica [*Rignot et al.*, 2001; *Thomas et al.*, 2004].

[3] The mechanism linking ice shelf retreat to climate change remains a matter of debate. It is assumed that melt ponding at the ice shelf surface plays an important role in the disintegration process [*Scambos et al.*, 2000]: the weight of the water column prevents crevasses from closing up so they can vertically penetrate the ice shelf. This theory is supported by satellite imagery showing elongated melt ponds on the surface of Larsen A and B ice shelves that drain into the sea shortly before their collapse [*Scambos et al.*, 2003]. Recent studies imply that ice shelf thinning through enhanced basal melting, either from oceanic warming and/or shifting ocean currents, speeds up ice shelf retreat [*Shepherd et al.*, 2003; *Bentley et al.*, 2005].

[4] Quantitative support for the melt pond theory is hampered by the scarcity of meteorological measurements. Here we quantify surface meltwater production on Larsen Ice Shelf (LIS) during the years preceding the collapse of Larsen B in March 2002. We use the only direct source of meteorological information from LIS, Larsen Ice automatic weather station (AWS, Figure 1), and assume the data to be representative for a large surrounding area. This is confirmed by passive microwave data, which show remarkably small latitudinal and longitudinal variability in melt season length over large areas of Larsen ice shelf [*Fahnestock et al.*, 2002; *Torinesi et al.*, 2003].

2. Data and Methods

2.1. AWS Data Selection and Treatment

[5] Larsen Ice AWS was installed in October 1985 by the United States Antarctic Program and is maintained by the British Antarctic Survey. Its location (67.01°S, 61.5°W, 17 m asl) is 200 km south of the centre of former Larsen B ice shelf. We use 10 min values of temperature, wind speed, wind direction and atmospheric pressure from the University of Wisconsin AWS data link (http://amrc.ssec.wisc.edu/aws.html). Data from the period March 1995–March 2003 were of sufficient quality for this study, except for the period July 1996 to January 1997 when the AWS wind sensor failed.

[6] LIS is a low wind speed site, and a correction was made for heating of the unventilated temperature sensor by solar radiation. As no radiation measurements are available, we use incoming solar radiation at the top of the atmosphere SW_{TOA} as a measure for radiation intensity. All $T >= 0$°C values were averaged in 1°C bins; bin averages for $T > 4$°C showed a clear preference for large SW_{TOA} and lower than average wind speed (V). These were assumed to represent excess heating, yielding an expression for the radiation error $dT = -2.09 + 0.220\,(SW_{TOA}/V)^{0.5}$, ($dT >= 0$ K and $dT <= 8$ K). After this correction, hourly averages were calculated if at least one 10 min sample was available. If hourly averages were missing during melting episodes, linear interpolation was used (<3% of the data).

2.2. Calculation of Melt Rate

[7] Surface melt rate equals $M\,L_f^{-1}$, where L_f is the latent heat of fusion and M is melting energy. We assume that

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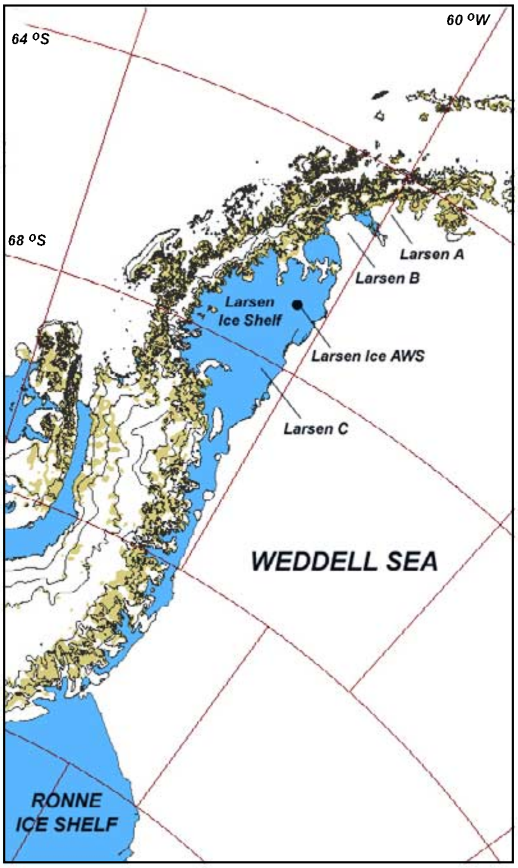

Figure 1. Map showing the locations of Larsen A, B and C and Larsen Ice AWS.

surface melting occurs if T >= 0°C at boom height [*van den Broeke et al.*, 2004]. M was calculated using:

$$M = SW_{net} + LW_{net} + SHF.$$

where SW_{net} is absorbed solar radiation at the surface, LW_{net} is net longwave radiation and SHF the turbulent flux of sensible heat. First, clear skies are assumed; if M < 0, it is assumed the sky was overcast. $SW_{net} = SW_{TOA}\ \tau\ (1 - \alpha)$ [W m^{-2}], where τ is atmospheric transmissivity for solar radiation and α is surface albedo. Based on measurements on Riiser Larsen Ice Shelf in Antarctica [*van den Broeke et al.*, 2004] we used $\tau = 0.75$ and $\alpha = 0.85$ for clear skies and $\tau = 0.55$ and $\alpha = 0.9$ for overcast conditions. Note that in regions where melt ponding occurs, α may be substantially reduced so our calculated meltwater production is a conservative estimate. $LW_{net} = 0.765\ \sigma\ T^4 - 315.6$ [W m^{-2}] (clear skies) or 0 (overcast). Following standard similarity theory, neglecting stability effects, $SHF = \rho\ c_p\ \kappa^2\ V\ T/\ln^2(z/z_0)$ where $c_p = 1005$ J kg^{-1} K^{-1} (specific heat of air at constant pressure) and Von Kármán's constant $\kappa = 0.4$. Surface roughness for momentum and heat $z_0 = z_h = 0.1$ mm and measuring height z = 3 m is assumed constant for wind speed and temperature. Air density ρ is calculated using AWS pressure and temperature. We neglect latent heat exchange and heat conduction in the snow based on the observation that during melting, moisture gradients between the surface and the atmosphere and temperature gradients in the snow pack are small.

3. Results

[8] The cumulative number of melt days (defined as days with T_{max} >= 0°C) is frequently used to denote melting in Antarctica, because it can be approximately measured using radar backscatter intensity and passive microwave data from satellites [*Abdalati and Steffen*, 1995]. At LIS, the 1995/96 to 2002/03 average number of melt days (from September 1st to August 31st) is 69, of which on average 50 occur in the summer months December–February. The 2001/02 melt season, during which Larsen B ice shelf collapsed, had 98 melt days, 53% more than the pre-2001/02 average. In cooler summers, melt is far from continuous, e.g. January 1998 only had 12 melt days.

[9] Unfortunately, the number of melt days is a poor indicator of meltwater production, because days with short

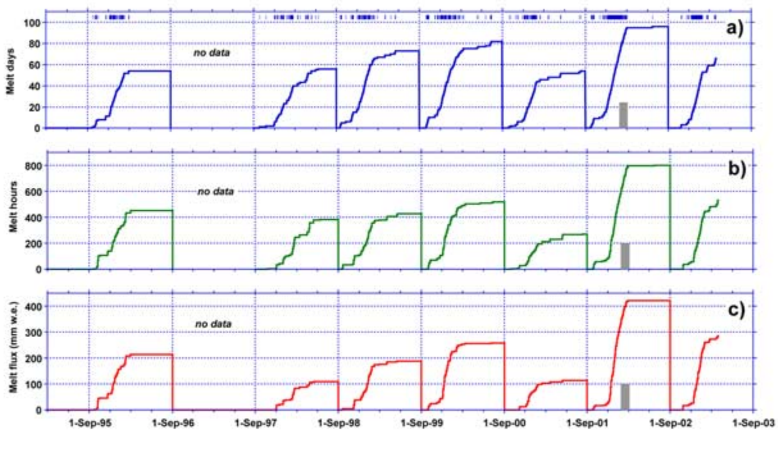

Figure 2. Larsen Ice AWS melting parameters, March 1995 to February 2003: (a) individual melt days (vertical thin bars) and cumulative amount of melt days (blue solid line); (b) cumulative amount of melt hours (green solid line) and (c) cumulative surface meltwater flux (mm water equivalent, red solid line)). For the cumulative numbers, counting starts on September 1st of each year. Grey bar indicates 2002 ice shelf collapse.

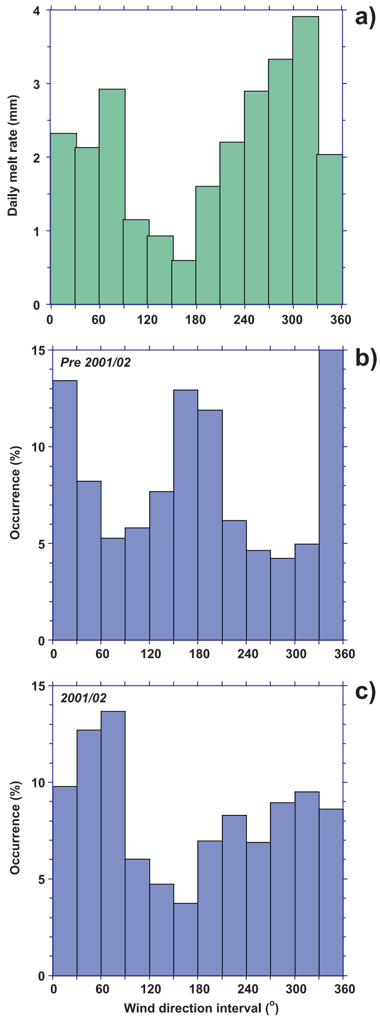

Figure 3. Larsen Ice AWS summer climate statistics (December–February): (a) average daily melt rate as a function of wind direction (all data), (b) pre-2001/02 wind direction distribution and (c) 2001/02 wind direction distribution.

and/or weak melting get the same weight as days with strong and/or continuous melting. A better index is the number of melt-hours (Figure 2b). The 2001/02 melt season now clearly stands out with 802 melt hours, 96% more than the pre-2001/02 average of 410 melt hours. This result shows that not only was the number of melt days above average in 2001/02, the melt duration on melt days also increased, from 6.4 to 8.2 hours.

[10] To further refine the calculation, the temporal distribution of melt hours over the day and season is taken into account; simple expressions for the magnitude of the energy fluxes at the atmosphere-ice shelf interface enables us to express the resulting index as a meltwater flux. The pre-2001/02 average meltwater flux of 176 mm yr^{-1} thus obtained (Figure 2c) is larger than the 1992–2001 average of 109 mm yr^{-1} calculated by *Shepherd et al.* [2003], based on a degree-day model. For 2001/02, the meltwater production of 422 mm yr^{-1} exceeds the average of the preceding years by a factor of 2.4 (140%). If only the summer period (December to February) is considered, the difference becomes even more pronounced (134 vs. 397 mm yr^{-1}, a factor of 3.0). Refining the calculation thus accentuates the exceptional nature of the 2001/02-melt season. Apart from the larger number of melt days and melt hours, the average melt rate in 2001/02 was also larger than the pre 2001/02 seasons, 0.53 compared to 0.43 mm per hour. This is caused by the fact that melting in 2001/02 was concentrated in summer, maximizing the availability of solar radiation.

[11] *Sergienko and MacAyeal* [2005] predict that 400 mm of meltwater is needed to fill crevasses on Larsen B ice shelf to 90% of their depth that enables them to propagate to the ice shelf base. Although we do not claim large absolute accuracy in the numbers presented above, it is remarkable that the 2001/02 cumulative surface melt in summer is equal to that number.

4. Discussion

[12] Meteorological conditions favourable for summertime melting are revealed if we consider melt rate as a function of wind direction (Figure 3a). A maximum melt rate of 4 mm per day occurs for flow from the NW, which represents a combination of warm air advection and a föhn effect caused by the mountains of the AP. A secondary melt rate maximum with values up to 3 mm per day is found for winds from the NE, where the likelihood of an ice-free sea is greatest. Lowest melt rates (less than 1 mm per day) occur during southerly flow, when cold air is transported from the Ronne Ice Shelf and the ice-covered, southern Weddell Sea. A weak secondary minimum in melt rate is found for northerly winds, advecting relatively cool ice shelf air.

[13] Figure 3b shows that the flow direction distribution during pre-2001/02 summers is unfavourable for melting: the predominantly southerly and northerly winds coincide with minimum melt rates in Figure 3a. In contrast, during the 2001/02 melt season (Figure 3c) LIS experienced winds

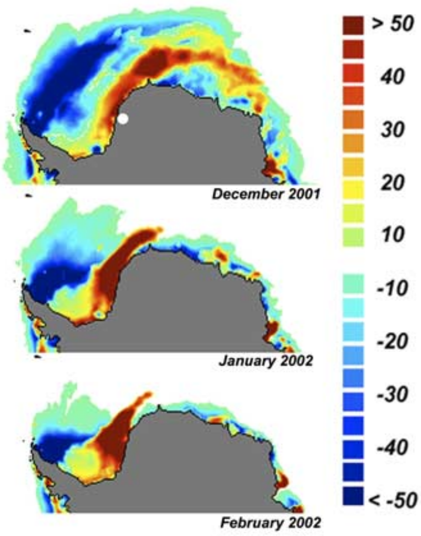

Figure 4. Monthly mean sea ice concentration anomalies (%) compared to 1979–2000. (source: National Snow and Ice Data Centre, USA). The location of Halley is indicated by a dot.

from sectors that are favourable for melting, the northwest and northeast. This anomalous atmospheric circulation affected large parts of the Weddell Sea, persisted throughout the summer and caused a large negative sea ice concentration anomaly in the northwestern Weddell Sea (Figure 4), starting right in front of LIS and extending hundreds of km northeastward. In combination with predominant winds from the northeast (Figure 3c), a transport of air over open water was maintained towards LIS throughout the 2001/02 summer, which explains the high temperatures and intensive, long duration melting. In the southeastern Weddell Sea (Figure 4), associated positive sea ice concentration anomalies prevented the relief of Halley Station (75.5°S, 26.4°W) for the first time since the International Geophysical Year in 1957/58 [*Turner et al.*, 2002].

[14] This result supports the importance of atmospheric circulation variability for near-surface Antarctic climate and the attribution of changes therein [*Thompson and Solomon*, 2002; *Kwok and Comiso*, 2002; *van den Broeke and van Lipzig*, 2003; *Marshall*, 2003].

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