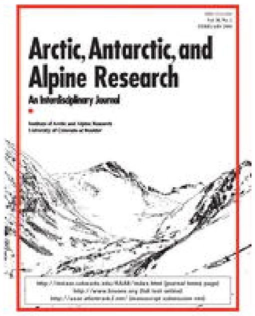

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Recent Trends in Melting Conditions on the Antarctic Peninsula and Their Implications for Ice-sheet Mass Balance and Sea Level

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Abstract

Long-term records from meteorological stations on the Antarctic Peninsula show strong rising trends in the annual duration of melting conditions. In each case, the trend is statistically significant and represents a major increase in the potential for melting; for example, between 1950 and 2000 the record from Faraday/Vernadsky Station showed a 74% increase in the number of positive degree-days (PDDs). A simple parameterization of the likely effects of the warming on the rate of snow melt suggests an increase across the Antarctic Peninsula ice sheet from 28 ± 12 Gt a^{-1} in 1950, to 54 ± 26 Gt a^{-1} by 2000. Given a similar rate of warming over the next 50 years this may reach 100 ± 46 Gt a^{-1}. The majority of this increased meltwater does not drain into the sea but is refrozen in the ice sheet, and it is difficult to predict the fraction of ablation that will become runoff; however, a calculation based on an established criterion for runoff indicates that the contribution from the Antarctic Peninsula, as a direct and immediate response to climate warming is significant, equivalent to (0.008–0.055) mm a^{-1} of global sea level rise. Given future warming this could easily treble in the coming 50 years. This contribution due to increased runoff could be augmented by any dynamic imbalance in the glaciers draining the ice sheet. This finding appears to contradict the conclusions of previous assessments, including the Intergovernmental Panel on Climate Change, which considered the contribution of runoff from Antarctica to sea level rise would be insignificant.

Introduction

Several studies have shown that over the period for which station measurements are available (approximately 50 years) there has been a recent rapid regional warming over the Antarctic Peninsula (e.g., King, 1994; Vaughan et al., 2003). Warming was particularly strong at Faraday/Vernadsky Station (Fig. 1) where mean annual temperature rose +5.7 ± 2.0°C per century, significant at the 1% level. However, stations on the west coast of the peninsula have also shown that the changes in mean annual temperature were dominated by winter warming (e.g., +11 ± 9°C per century at Faraday/Vernadsky), and although summer warming was usually significant at the 1% level, it was considerably less (only +2.4 ± 1.7°C per century at Faraday/Vernadsky; Vaughan et al., 2003).

Summer temperatures on the Antarctic Peninsula are, however, close to melting and so even a small degree of warming may have significant impacts. Indeed, there are many reports that summer warming has reduced seasonal snow cover (Fox and Cooper, 1998), altered the mass balance and thermal regime of the permanent ice cover (e.g., Smith et al., 1998), promoted the expansion of biological habitats (Lewis, 1994) and caused the retreat of ice shelves (Vaughan and Doake, 1996; Scambos et al., 2000; Morris and Vaughan, 2003).

In this paper I use temperature data from Antarctic Peninsula meteorological stations to investigate the increase in the annual duration of above-freezing conditions. I show positive trends in the number of positive degree-days per year measured at every station for which sufficient data are available to make an estimate. In each case the trend is statistically significant and represents a substantial increase in the potential for melting. To highlight the potential importance of the impacts of this change on one aspect of the local environment, I investigate the degree to which the warming has caused an increase in surface ablation over the Antarctic Peninsula ice sheet. The study shows that the potential contribution to sea level rise from this area, whether climate is maintained in its current state, or with continued warming on the Antarctic Peninsula, may be significantly greater than has been previously thought.

Geographic Context

The Antarctic Peninsula is quite different from the rest of the continental ice sheet; while it accounts for only ~2% of the total area of the entire grounded Antarctic ice sheet, it receives ~7% of the snowfall (equivalent to ~0.37 mm a^{-1} of global sea level change; Vaughan et al., 1999). And arguably, it has greater similarity to subpolar glacial systems (such as coastal Greenland, Svalbard, Patagonia, and Alaska), which are known to be more sensitive to atmospheric warming, than to the cold ice sheets covering the rest of the Antarctic continent, which are usually considered insensitive (Church et al., 2001). Furthermore, in contrast to those homogenous ice sheets, the ice covering the Antarctic Peninsula consists of more than 400 largely independent mountain glaciers draining into ice shelves or through marine tidewater glaciers, with just a handful terminating on land. This steep topography and the sinuous nature of the coastline means that this area is poorly represented in continent-scale ice-sheet models, and those models do not resolve the near-coastal zones of melting. Thus, while runoff is generally considered to be an insignificant component in the mass balance of the entire Antarctic ice sheet (e.g., Church et al., 2001), it is possible that runoff from the Antarctic Peninsula, as a direct and immediate response to recent climate change, may be larger than has been previously estimated.

Trends in Positive Degree-Days (PDDs)

Several meteorological stations on the Antarctic Peninsula provide year-round observations. Data used in this study were extracted

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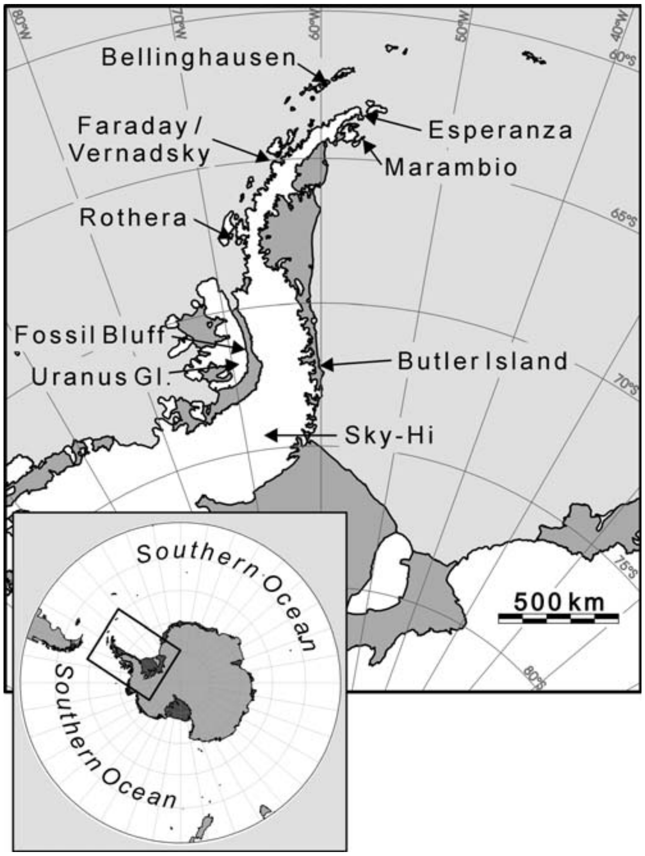

FIGURE 1. Location map for the Antarctic Peninsula. Areas of floating ice shelves have darkest shading.

from the British Antarctic Survey archive of meteorological observations (http://www.antarctica.ac.uk/met/metlog/), which acquires data directly from research stations in Antarctica and from the World Meteorological Organization, Global Telecommunications System. In each case, data at the highest temporal resolution available was used (usually, 6-hourly or 3-hourly, but hourly for some of the later records), and records that were significantly incomplete were discarded. For each station, I calculated the sum of positive degree days, Φ_n, for austral melt season, n, using the sequence of measurements, i, according to the following,

$$\begin{aligned} \Phi_n = \sum_{i\,=\,June,\,22,\,year\ n-1}^{i\,=\,June,\,21,\,year\ n} T_i(t_{i+1} - t_i)\ \alpha(T_i) \\ where, \quad \alpha(T_i) = 1, \quad if\ T_i > 0^{\circ}\mathrm{C} \\ \alpha(T_i) = 0, \quad if\ T_i < 0^{\circ}\mathrm{C}. \end{aligned} \tag{1}$$

Here, T_i is the station surface temperature in °C, t_i is the time expressed in days and fractions thereof, and α is the binary function expressing whether or not melt will occur. It should be noted that while many studies have previously used mean-daily, or even mean-monthly temperatures as the metric of melt estimation, I have used all 6-hourly to 1-hourly temperature records. This gives a far more sensitive evaluation of the potential for melt than methods based on mean daily or monthly records.

Figure 2 shows the annual PDD series for three stations on the Antarctic Peninsula (Faraday/Vernadsky, Rothera, and Bellingshausen) for which there are sufficient data to derive long-term trends, and stations (Esperanza, Marambio, Fossil Bluff, and Butler Island automatic weather station [AWS], Uranus Glacier AWS, and Sky-Hi AWS) for which there are insufficient data to determine a trend of

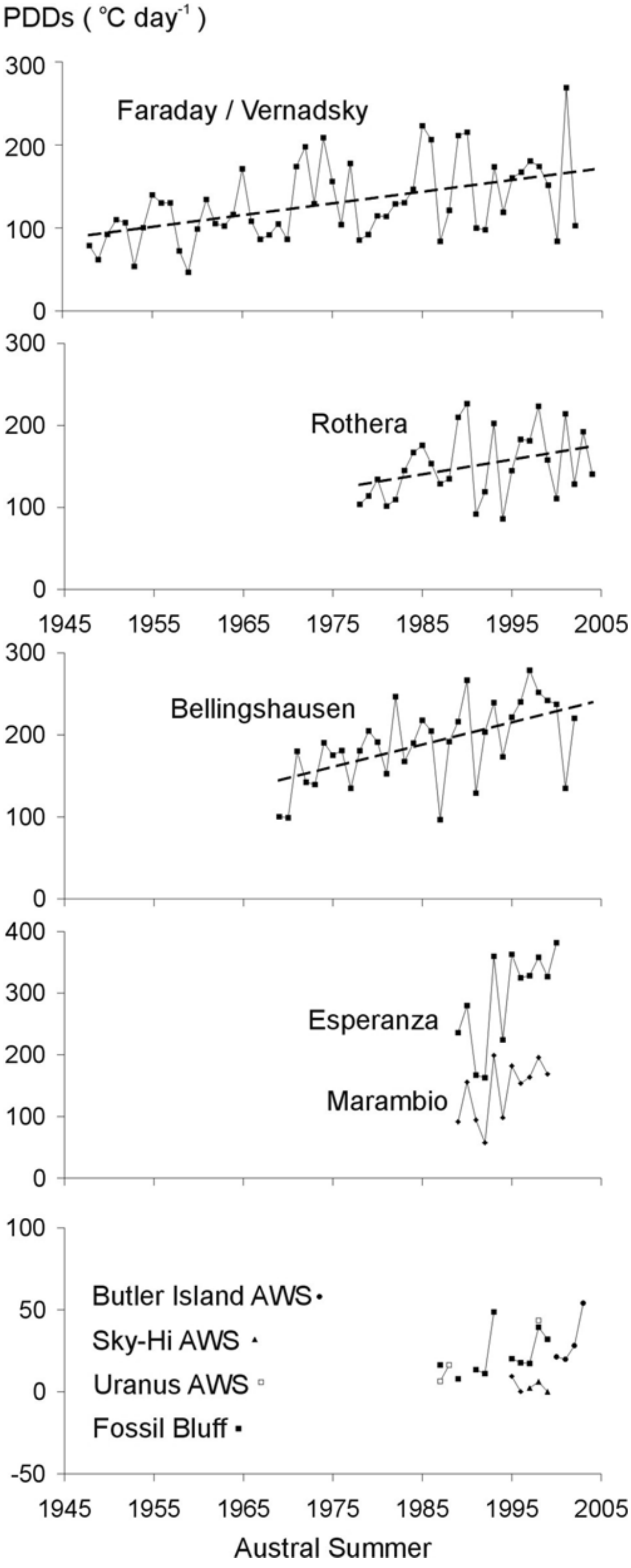

FIGURE 2. Annual positive degree-days from temperature records at Faraday/Vernadsky, Rothera, Esperanza, Bellingshausen, Marambio, Fossil Bluff, Butler Island AWS, Shy-Hi AWS, and Uranus Glacier AWS. Trend lines are given for the three long-term records (for regression values and significance, see Table 1). Data from the four others sites is shown for completeness as it is included in the parameterization shown in Figure 3.

TABLE 1

Trends in the annual occurrence of positive-degree days at three stations on the Antarctic Peninsula. The uncertainty in trend is quoted at the 95% level, and together with the significance, was calculated using a method which takes account of autocorrelation in the time series (Santer et al., 2000).

Station	Trend/PDDs* per year	Significance	Period/years
Faraday/Vernadsky	1.4 ± 0.7	<0.1%	55
Rothera	1.8 ± 1.7	<5%	27
Bellingshausen	2.7 ± 1.3	<0.1%	34

* PDDs = positive degree-days.

any interpretable significance. Each long-term station shows strong interannual variability, but the trend in PDDs per year is, in each case, highly significant (see Table 1).

Not only is the trend statistically significant, but the percentage increase within the period is dramatic and represents a substantial increase in the potential for melting. For example, at Faraday/Vernadsky, between 1950 and 2000, the trend line indicates a 74% increase in the number of PDDs. Similarly, the annual average for PDDs at Rothera and Bellingshausen rose by 14% and 18.5% per decade over the period of measurement (over 5 decades this would amount to similar values as that for Faraday/Vernadsky).

It is also notable (see Table 2) that there is some interannual correlation between the stations on the sites on the west coasts (Rothera and Faraday/Vernadsky) and the sites on the east coast (Esperanza and Marambio). This suggests that the trends are probably widespread across the Antarctic Peninsula. Although the correlation is quite poor between Faraday/Vernadsky and Rothera, and Bellingshausen, they share several high- and low-PDD years.

Surface Melting

Much has been written about the most accurate methods of modeling surface mass balance through energy-balance approaches (e.g., Greuell and Genthon, 2003), but the data required to pursue these approaches over a long period are not often available. For this reason, many researchers have relied on simpler temperature-based melt-index methods which have been shown to have a reasonable simulation capacity (for summaries, see Ohmura, 2001; Hock, 2003). Other correlations have been sought, but have usually been shown to be inferior; for example, Szafraniec (2002) showed that duration of sunshine was an inferior predictor of ablation compared to PDDs. In this study, I estimate changes in surface ablation using PDDs as the metric, and then estimate the increased ablation that is occurring on the Antarctic Peninsula as a result of the rapid regional warming over the past 50 years, and the likely consequences if this warming continues.

The analysis is based on a 1000-m resolution version of the digital elevation model (DEM) of the Antarctic Peninsula produced by Liu et al. (1999). For the centre point of each pixel in the DEM, the mean annual temperature at sea level for A.D. 2000 was extracted from a recent interpolation of observations by Morris and Vaughan (2003), which incorporated over 500 individual measurements and analyzed them through a multiple-regression that took account of latitude, elevation, secular trend, and the differences between the east and west coast. I used an altitudinal lapse rate derived in that study (–0.0044°C m^{-1}) to convert this sea level temperature to a surface temperature. Figure 3 shows that on each coast of the Antarctic Peninsula, there is a reasonable correlation between mean annual air temperature and the annual number of PDDs. The exponential regression lines shown in Figure 3 were used as parameterizations to convert the map of mean annual surface temperature into a map of the annual number of PDDs (Fig. 4b) for year 2000.

TABLE 2

Correlation coefficients (r^2) between stations on the Antarctic Peninsula: mean annual temperature, positive-degree days, number of common years.

	Rothera	Bellingshausen	Esperanza	Marambio
Faraday/Vernadsky	0.90, 0.69, 25	0.40, 0.08, 34	0.38, 0.08, 12	0.32, 0.27, 11
Rothera		0.42, 0.19, 25	0.18, 0.37, 12	0.40, 0.35, 11
Bellingshausen			0.82, 0.51, 12	0.52, 0.42, 11
Esperanza				0.40, 0.92, 11

Similar maps to represent 1950 and 2050 were constructed by assuming mean annual temperatures uniformly 2.5°C cooler than 2000, and uniformly 2.5°C warmer than 2000, respectively (Figs. 4a, c).

To use these maps of PDDs to estimate changes in ablation required a "PDD-factor" (Braithwaite, 1995). Several authors have compared PDD-factors obtained by various researchers in different geographical areas. For snow-covered areas, Braithwaite (1995) showed a mean PDD-factor of 4.3 ± 1.0 kg m^{-2} $°C^{-1}$ day^{-1}; the result given by Hock (2003) suggests an average of 4.7 ± 2.2 kg m^{-2} $°C^{-1}$ day^{-1}. More recent work on Svalbard confirmed that values in the range 6 to 7 kg m^{-2} $°C^{-1}$ day^{-1} were appropriate (Szafraniec, 2002). The limited data available for the Antarctic Peninsula summarized by Smith et al. (1998) similarly suggest mean values between 2.17 and 6 kg m^{-2} $°C^{-1}$ day^{-1}. A more recent study from Moraine Corrie suggested 33 ± 8 kg m^{-2} $°C^{-1}$ day^{-1} (Morris, 1999); however, it was accepted that this was a particularly high value, probably resulting from the unusually sheltered location surrounded by dark rock walls. By and large, these observational values compare well with a tuned modeling study on Greenland that indicated values in a range 3 to 8 kg m^{-2} $°C^{-1}$ day^{-1} were appropriate on the lower portions of the ice sheet, although rather larger values were appropriate on the higher zones (Lefebre et al., 2002).

It has been noted that there is both spatial and regional variation in the magnitude of PDD-factors (Hock, 2003) and that a high-resolution study should take account of both, but the quality of data available for the Antarctic Peninsula means that for the present, a rough estimate

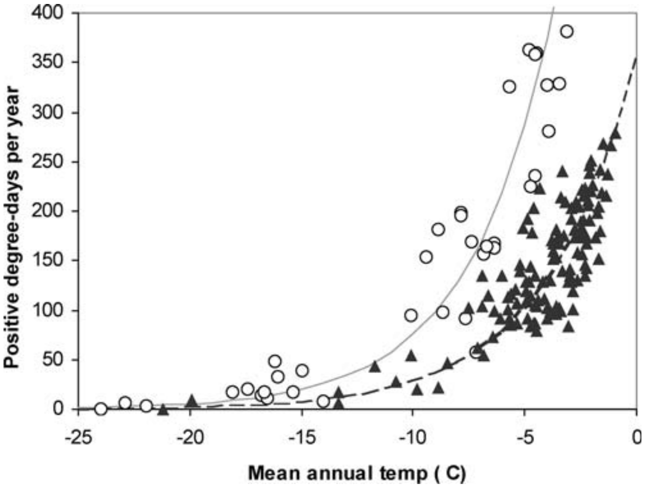

FIGURE 3. Correlation of mean annual air temperature to positive degree-days for all Antarctic Peninsula station data. East coast sites are represented by open circles and have a best fit regression line (solid) of $\Phi = 1089\ e^{(0.261T/°C)}$ ($r^2 = 0.84$). West coast sites are represented by black triangles and have a best-fit regression line (dashed) of $\Phi = 358\ e^{(0.251T/°C)}$ ($r^2 = 0.79$).

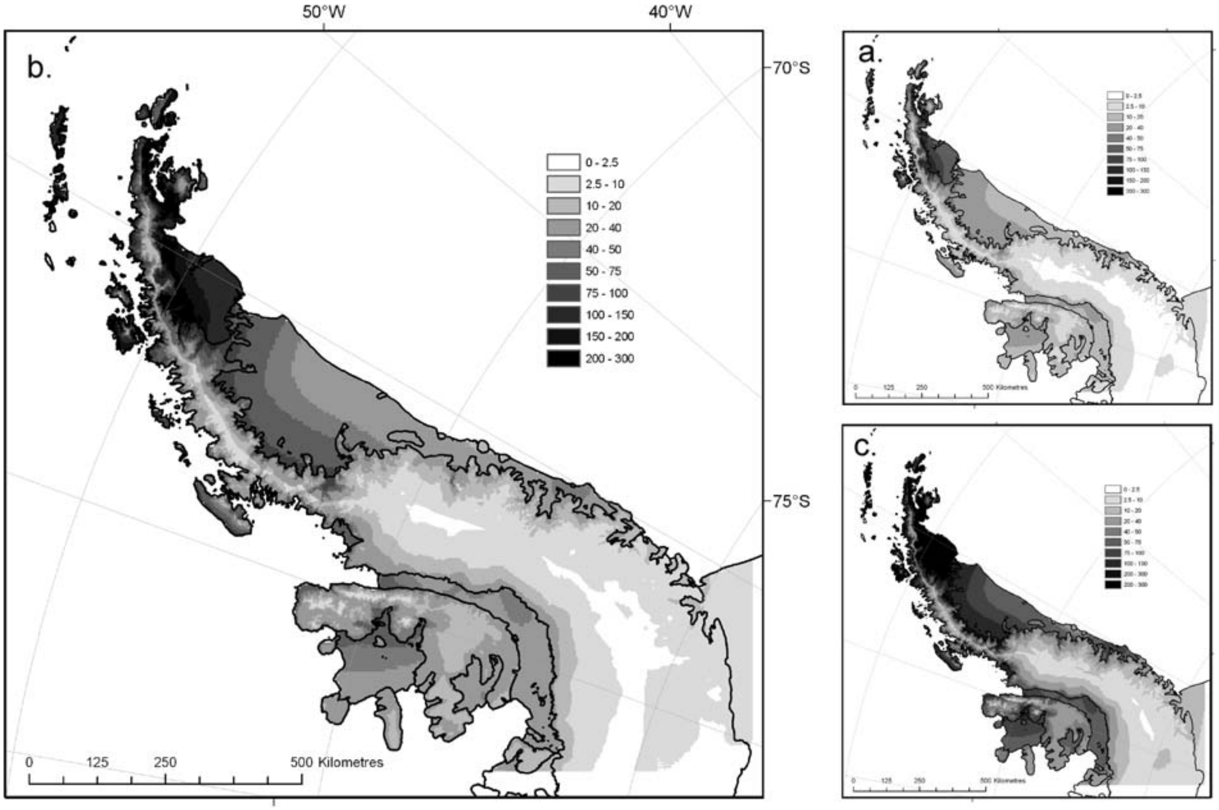

FIGURE 4. Distribution of annual positive degree-days calculated for (a) 1950 (i.e., 2000 − 2.5°C), (b) 2000, and (c) 2050 (i.e., 2000 + 2.5°C).

using a single range of PDD-factors is the best that can be achieved. Given the likelihood that the Antarctic Peninsula may have systematically different partitioning of energy balance components, and different snow conditions, I adopted a conservative range in the mean PDD-factors that brackets the observations and matches the range derived from the modeling, i.e., 3 to 8 kg m^{-2} $°C^{-1}$ day^{-1}. Applying this range of PDD-factors produced surface ablation integrated over the area shown in Figure 4 (Table 3). This clearly indicates the significance of likely changes over the last 50 years, and a substantial increase if warming continues in the coming 50 years.

Runoff

The calculated increase in ablation presented in the previous section is an important variable, but is not a direct measure of the contribution to sea level rise, and several factors make this a difficult quantity to estimate.

First, it must be noted that not all of the summer melt would become runoff (meltwater which reaches the sea without refreezing); a significant fraction will be refrozen and remain in the snow pack, although in the long-term if sufficient melt is produced, the ice sheet may be driven to temperate conditions and refreezing will be much reduced. Second, there are effects that magnify the contribution to sea level over simple runoff. Increased lubrication due to surface meltwater reaching the ice sheet base is known to increase glacier flow speeds (Zwally et al., 2002), and there is emerging evidence for such acceleration on the Antarctic Peninsula (Pritchard, British Antarctic Survey, personal communication). Similarly, the loss of ice shelves due to atmospheric warming has resulted in a reduction in restraint and caused glaciers to accelerate (De Angelis and Skvarca, 2003; Rignot et al., 2004).

On the other hand, climate change might alter the rate of precipitation (the frequency of precipitation events has been shown to be increasing; Turner et al., 1997) over the area and tend to balance the summer melt with additional snowfall. This might reduce the impact of increased ablation if it falls as snow, or exacerbate it if it falls as rain.

A full assessment of the contribution of the Antarctic Peninsula ice sheet to sea level rise will thus require a complex model that includes detailed climatic considerations and ice dynamical effects, which is beyond the scope of the present study. There follows simply an estimate of the contribution resulting only from increased melting and runoff.

Pfeffer et al. (1991) suggested that runoff will begin when the annual amount of surface melt generated is sufficient to allow motion of water in the firn: (1) enough water must refreeze in the initially subfreezing firn to bring the snow temperature to 0°C, and (2) after the firn temperature is raised to the melting point, additional melt must be supplied to raise the pore water content of the firn to the minimum value to allow water motion over capillary forces. Thus, runoff can begin once sufficient annual melt (M_0) is produced to satisfy these conditions, i.e.,

$$M_0 = \frac{c}{L} C T_f + (C - M)\left(\frac{\rho_{pc} - \rho_c}{\rho_c}\right), \tag{2}$$

where C is the annual accumulation, c and L are the heat capacity and latent heat of fusion for ice, and T_f is the temperature of the firn at the time that the meltwater first comes into contact with it. The initial firn density, ρ_c, is taken as 400 kg m^{-3}, and the pore close-off density, ρ_{pc}, is taken as 830 kg m^{-3}. This implies that, if the total annual surface ablation is M, the amount of water available for runoff, R, is

$$R = M - M_0 = M - (0.003 T_f + 0.52) C. \tag{3}$$

This value was calculated for each point in the grid described above using as input another grid representing surface accumulation rate, C, produced by a 14-km resolution regional general circulation model (GCM; van Lipzig et al., 2005). Since there are no high-resolution GCM predictions for how the accumulation rate has changed, or will change, on the Antarctic Peninsula, I have used a constant accumulation rate field in this study, and note that substantial secular changes in the accumulation might alter the results. The precise definition of the initial firn temperature, T_f, is clearly defined and would be reasonably approximated to the temperature in the snow pack at the start of the melt season. Such a value is, however, extremely difficult to estimate. Here I used the value of the mean annual air temperature in place of T_f and note that this is a conservative assumption that will tend to underestimate the runoff. However, Equation 3 shows that saturating each year's accumulation generally takes more energy than warming the snow pack, and the likely error in this estimation in T_f does not have a substantial effect on the overall volume of runoff.

The volume of runoff calculated in this way is, unsurprisingly, much less than the total amount of surface melt, but is nevertheless significant (Table 3). It should be noted that the upper estimates for runoff in 2000 and 2050 are equivalent to only 11% and 27% of the yearly total snow accumulation for the Antarctic Peninsula, respectively (given by areas H to J *in* Vaughan et al., 1999). Note that the range given in the table is derived only from the range of PDD-factors and does not include uncertainty in the accumulation rate field, non-equilibrium effects, or uncertainties in the applicability of the runoff calculation. In each case the lower side of the estimate that arises from the low PDD-factor (3 kg m^{-3} PDD^{-1}) is much lower than that arising from the upper estimate (8 kg m^{-3} PDD^{-1}), which indicates a highly non-linear response to changes in this parameter.

Conclusions

The study presented has four distinct parts. (1) The analyses of long-term meteorological station data, which show the increase in the duration of melt conditions across the Antarctic Peninsula over the past 50 years, which is substantial and significant. The rate of increase at Faraday/Vernadsky suggests an increase of 74% between 1950 and 2000, with similar rates measured at the other stations. (2) The analysis of data acquired from meteorological stations and AWS, which has allowed a parameterization of the number of PDDs as a function of mean annual temperature. (3) The estimation of annual surface ablation based on this parameterization and its likely changes as a result of past and future climate change, which has shown that surface ablation is likely to have doubled between 1950 and 2000, and given continued summer warming could double or treble by 2050. (4) The estimation of the fraction of this surface ablation that could become runoff. Given that 360 Gt of water is equivalent to global sea level rise of around 1 mm (Jacobs et al., 1992), the rates of runoff in 2000 could already produce the equivalent of (0.008–0.055) mm a^{-1} of sea level rise with the likelihood that with continued warming this would rise considerably, perhaps trebling within 50 years.

The decreasing confidence we can apply to the conclusions derived from each of these steps is a good example of a "cascade of uncertainty" (Schneider, 1983). The analyses of observations in (1) are based on sound data and are robust, the parameterization (2) is justifiable on the basis of the data but is clearly a simplification of real world, the estimate of increased surface ablation (3) is qualitatively realistic but contains substantial quantitative uncertainty due to the model assumptions, and the estimate of the runoff (4) can probably only be taken as an order-of-magnitude estimate since it incorporates a further set of assumptions and simplifications. However, this final step is nevertheless justified, in that it signals the importance of the potential contribution to sea level rise and of the need for a concentrated effort in this area to constrain the magnitude of this contribution more rigorously.

TABLE 3

Comparison of mean model results for the grounded portion of the Antarctic Peninsula. Note that the quoted uncertainty in surface melt and range of runoff estimates are due solely to the range of PDD* factor used in the calculation; they do not include uncertainties due to inadequacies in the model assumptions.

	Mean positive degree-days per year	Total surface melt (Gt a^{-1})	Total runoff (Gt a^{-1})
1950	14.2	28 ± 12	0.54–5.8
2000	27.1	54 ± 26	2.9–20
2050	54.8	100 ± 46	3.0–56

* PDD = positive degree-day.

This requirement is further highlighted through comparison to another subpolar glacial system which is suffering unusual rates of atmospheric warming, the 90,000 km^2 of Alaskan glaciers. Understanding of this area has undoubtedly progressed by a coherent measurement campaign, and Alaska is now the "largest glaciological contribution to rising sea level yet measured" (Arendt et al., 2002). Over the period from the mid-1990s to 2000, changes in Alaska probably contributed 0.27 ± 0.10 mm a^{-1} to sea level rise. For comparison, the Antarctica Peninsula supports 120,000 km^2 of grounded ice sheet whose lower reaches suffer substantial melt, and 45,000 km^2 lies below 200 m above sea level. Furthermore, the warming over the Antarctic Peninsula has arguably been stronger and more persistent than in Alaska.

Furthermore, my upper estimate of the contribution to sea level rise from the Antarctic Peninsula in 2050 (0.16 mm a^{-1}) probably cannot be considered as negligible compared to the Intergovernmental Panel on Climate Change (IPCC) estimate of the contribution of the entire Antarctic ice sheet (–0.072 mm a^{-1} for the period 1990–2100; Table 11.14 *in* Church et al., 2001). Thus the statement by the IPCC, that "Antarctic temperatures are so low that there is virtually no surface runoff" (Church et al., 2001) needs to be revisited.

Similarly, an earlier assessment by Drewry and Morris (1992) could be several times too low. They estimated that a 2°C rise in mean annual temperature over 40 years would cause an increase in runoff sufficient to raise sea level by only 1.0 mm. The central estimates produced here suggest that the contribution of runoff could be in the range (0.3–4.0) mm over the same period. Given that this contribution will augment the contribution arising from glacier acceleration, which is known to be underway, and the case for a systematic program of observations on the Antarctic Peninsula is a strong one.

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References Cited

Arendt, A. A., Echelmeyer, K. A., Harrison, W. D., Lingle, C. S., and Valentine, V. B., 2002: Rapid wastage of Alaska glaciers and their contribution to rising sea level. *Science,* 297: 382–386.

Braithwaite, R. J., 1995: Positive degree-day factors for ablation on the Greenland ice sheet studied by energy-balance modelling. *Journal of Glaciology,* 41: 153–160.

Church, J. A., Gregory, J. M., Huybrechts, P., Kuhn, M., Lambeck, K., Nhuan, M. T., Qin, D., and Woodworth, P. L., 2001: Changes in sea level. *In* Houghton, J. T., Ding, Y., Griggs, D. J., Noguer, M., van den Linden, P. J., Dai, X., Maskell, K., and Johnson, C. A. (eds.), *Climate Change 2001: The Scientific Basis.* Cambridge: Cambridge University Press, 583–638.

De Angelis, H., and Skvarca, P., 2003: Glacier surge after ice shelf collapse. *Science,* 299: 1560–1562.

Drewry, D. J., and Morris, E. M., 1992: The response of large ice sheets to climatic change. *Philosophical Transactions of the Royal Society of London, Series B,* 338: 235–242.

Fox, A. J., and Cooper, A. P. R., 1998: Climate-change indicators from archival aerial photography of the Antarctic Peninsula. *Annals of Glaciology,* 27: 636–642.

Greuell, W., and Genthon, C., 2003: Modelling land-ice surface mass balance. *In* Bamber, J. L., and Payne, A. J. (eds.), *Mass Balance of the Cryosphere: Observations and Modelling of Contemporary and Future Changes.* Cambridge: Cambridge University Press, 117–168.

Hock, R., 2003: Temperature index melt modelling in mountainous areas. *Journal of Hydrology,* 282: 104–115.

Jacobs, S. S., Helmer, H. H., Doake, C. S. M., Jenkins, A., and Frolich, R. M., 1992: Melting of ice shelves and the mass balance of Antarctica. *Journal of Glaciology,* 38: 375–387.

King, J. C., 1994: Recent climate variability in the vicinity of the Antarctic Peninsula. *International Journal of Climatology,* 14: 357–369.

Lefebre, F., Gallee, H., Van Ypersele, J. P., and Huybrechts, P., 2002: Modelling of large-scale melt parameters with a regional climate model in south Greenland during the 1991 melt season. *Annals of Glaciology,* 35: 391–397.

Lewis, S. R., 1994: Vascular plants as bioindicators of regional warming in Antarctica. *Oecologia,* 99: 322–328.

Liu, H. X., Jezek, K. C., and Li, B., 1999: Development of Antarctic DEM by integrating cartographic and remotely sensed data: A GIS-based approach. *Journal of Geophysical Research,* 104: 23199–23213.

Morris, E. M., 1999: Surface ablation rates on Moraine Corrie Glacier, Antarctica. *Global and Planetary Change,* 22: 221–231.

Morris, E. M., and Vaughan, D. G., 2003: Spatial and temporal variation of surface temperature on the Antarctic Peninsula and the limit of viability of ice shelves. *In* Domack, E., Leventer, A., Burnett, A., Bindschadler, R., Convey, P., and Kirby, M. (eds.), *Antarctic Peninsula climate variability: historical and paleoenvironmental perspectives.* Washington, DC: American Geophysical Union, *Antarctic Research Series,* 79: 61–68.

Ohmura, A., 2001: Physical basis for the temperature-based melt-index method. *Journal of Applied Meteorology,* 40: 753–761.

Pfeffer, W. T., Meier, M. F., and Illangasekare, T. H., 1991: Retention of Greenland runoff by refreezing: implications for projected future sea level change. *Journal of Geophysical Research,* 96: 22117–22124.

Rignot, E., Casassa, G., Gogineni, P., Krabill, W., Rivera, A., and Thomas, R., 2004: Accelerated ice discharge from the Antarctic Peninsula following the collapse of Larsen B ice shelf. *Geophysical Research Letters,* 31: doi:10.1029/2004GL020679.

Santer, B. D., Wigley, T. M. L., Boyle, J. S., Gaffen, D. J., Hnilo, J. J., Nychka, D., Parker, D. E., and Taylor, K. E., 2000: Statistical significance of trends and trend differences in layer-average temperature time series. *Journal of Geophysical Research,* 105: 7337–7356.

Scambos, T. A., Hulbe, C., Fahnestock, M., and Bohlander, J., 2000: The link between climate warming and break-up of ice shelves in the Antarctic Peninsula. *Journal of Glaciology,* 46: 516–530.

Schneider, S. H., 1983: CO_2, climate and society: a brief overview. *In* Chen, R. S., Boulding, E., and Schneider, S. H. (eds.), *Social Science Research and Climate Change: In Interdisciplinary Appraisal.* Boston, Massachusetts, U.S.A.: D. Reidel, 9–15.

Smith, A. M., Vaughan, D. G., Doake, C. S. M., and Johnson, A. C., 1998: Surface lowering of the ice ramp at Rothera Point, Antarctic Peninsula, in response to regional climate change. *Annals of Glaciology,* 27: 113–118.

Szafraniec, J., 2002: Influence of positive degree-days and sunshine duration on the surface ablation of Hanbreen, Spitsbergen glacier. *Polish Polar Research,* 23: 227–240.

Turner, J., Colwell, S. R., and Harangozo, S., 1997: Variability of precipitation over the coastal western Antarctic Peninsula from synoptic observations. *Journal of Geophysical Research,* 102: 13999–14007.

van Lipzig, N. P. M., King, J. C., Lachlan-Cope, T. A., and van den Broeke, M. R., 2005: Precipitation, sublimation and snow drift in the Antarctic Peninsula region from a regional atmospheric model. *Journal of Geophysical Research,* 109: doi 10.1029/2004JD004701.

Vaughan, D. G., and Doake, C. S. M., 1996: Recent atmospheric warming and retreat of ice shelves on the Antarctic Peninsula. *Nature,* 379: 328–331.

Vaughan, D. G., Bamber, J. L., Giovinetto, M., Russell, J., and Cooper, A. P. R., 1999: Reassessment of net surface mass balance in Antarctica. *Journal of Climate,* 12: 933–945.

Vaughan, D. G., Marshall, G. J., Connolley, W. M., Parkinson, C. L., Mulvaney, R., Hodgson, D. A., King, J. C., Pudsey, C. J., and Turner, J., 2003: Recent rapid regional climate warming on the Antarctic Peninsula. *Climatic Change,* 60: 243–274.

Zwally, H. J., Abdalati, W., Herring, T., Larson, K., Saba, J., and Steffen, K., 2002: Surface melt-induced acceleration of Greenland ice-sheet flow. *Science,* 297: 218–222.

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