An updated Antarctic melt record through 2009 and its linkages to high-latitude and tropical climate variability

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[1] A 30-year minimum Antarctic snowmelt record occurred during austral summer 2008–2009 according to spaceborne microwave observations for 1980–2009. Strong positive phases of both the El-Niño Southern Oscillation (ENSO) and the Southern Hemisphere Annular Mode (SAM) were recorded during the months leading up to and including the 2008–2009 melt season. The 30-year record confirms that significant negative correlations exist at regional and continental scales between austral summer melting and both the ENSO and SAM indices for October–January. In particular, the strongest negative melting anomalies (such as those in 2008 and 2009) are related to amplified large-scale atmospheric forcing when both the SAM and ENSO are in positive phases. Our results suggest that enhanced snowmelt is likely to occur if recent positive summer SAM trends subside in conjunction with the projected recovery of stratospheric ozone levels, with subsequent impacts on ice sheet mass balance and sea level trends. **Citation:** Tedesco, M., and A. J. Monaghan (2009), An updated Antarctic melt record through 2009 and its linkages to high-latitude and tropical climate variability, *Geophys. Res. Lett.*, *36*, L18502, doi:10.1029/2009GL039186.

1. Introduction

[2] Snowmelt in Antarctica can be estimated with spaceborne passive microwave sensors because of the abrupt and significant increase in the measured signal coincident with the appearance of liquid water in snow [e.g., *Ulaby and Stiles*, 1980; *Tedesco et al.*, 2006; *Tedesco*, 2009]. The sign of the melting trends has been regionally variable and dependent on the period analyzed and on the indices used, with the continent-averaged trend being small and generally statistically in significant [*Torinesi et al.*, 2003; *Liu et al.*, 2006; *Picard et al.*, 2007; *Tedesco*, 2009]. Here we extend the results reported by *Tedesco* [2009] through the 2008–2009 austral summer and derive updated 1980–2009 trends from near-daily records of microwave brightness temperatures (T_b) at K-band, horizontal polarization, measured by the Scanning Multichannel Microwave Radiometer (SMMR, 1980–1987) and by the Special Sensor Microwave Imager (SSMI, 1988–2009). We use the EASE-Grid T_b record distributed by the National Snow and Ice Data Center (http://nsidc.org/data/nsidc-0032.html, http://nsidc.org/data/nsidc-0071.html). Further, we employ the new 30-year record to examine the robustness of statistical linkages between snowmelt and the SAM and ENSO indices, expanding on previous work that used a shorter (20-year) record [*Torinesi et al.*, 2003].

[3] The SAM is a measure of the pressure gradient between the Southern Hemisphere middle and high latitudes [e.g., *Thompson and Wallace*, 2000]. ENSO is an ocean-atmosphere oscillation manifested in shifting sea surface temperature anomalies in the tropical Pacific Ocean, and its variability is often measured by the 'see-saw' of surface pressure anomalies between Tahiti and Darwin, known as the Southern Oscillation Index (SOI). The SAM and ENSO have important impacts on Antarctic climate and have been shown to influence near-surface temperatures [e.g., *Yuan and Martinson*, 2001; *Thompson and Solomon*, 2002; *Bromwich et al.*, 2004; *Turner*, 2004; *van den Broeke and van Lipzig*, 2004; *Marshall*, 2007]. However, snowmelt variability does not coincide exactly with temperature fluctuations because the components of the surface energy balance combine in non-linear ways to influence melt [e.g., *Liston and Winther*, 2005]. Therefore, addressing directly the linkages between snowmelt and the SAM and ENSO is important.

2. Methods and Results

2.1. The 2009 Minimum and the 1980–2009 Updated Trends

[4] According to the physically-driven approach reported by *Tedesco* [2009] named MEMLS2, Antarctic snowmelt index in 2009 (e.g., the number of melting days times the area subject to melting with the year referring to the January of a reported melt season, but including melt from November and December of the previous year) set a new historical minimum for the period 1980–2009 (Figure 1). In MEMLS2, melting is detected when T_b at K-band, horizontal polarization, exceeds a threshold value T_c, computed as a function of the dry snow T_b using the outputs of a multilayer electromagnetic model. The snowmelt index in 2009 was about ~17.8 million km^2 × days, below the average (1980–2008) value of about 35 million km^2 × days. Snowmelt extent in 2009 was ~690,000 km^2, also significantly smaller than the average value of ~1,294,000 km^2, being the second lowest value in the 30-year record (Figure 1).

[5] Despite the extremely strong negative melting anomalies occurring over the Wilkins ice shelf in 2009 (~−20 days, Figure 2a), this area experienced the highest number of melting days across Antarctica (~90 days, Figure 2b), consistent with other recent years [*Tedesco*, 2009]. The strong surface melting coincides with the most recent collapse event on the Wilkins ice shelf, which began in February 2008 [e.g., *Braun et al.*, 2008] and underwent

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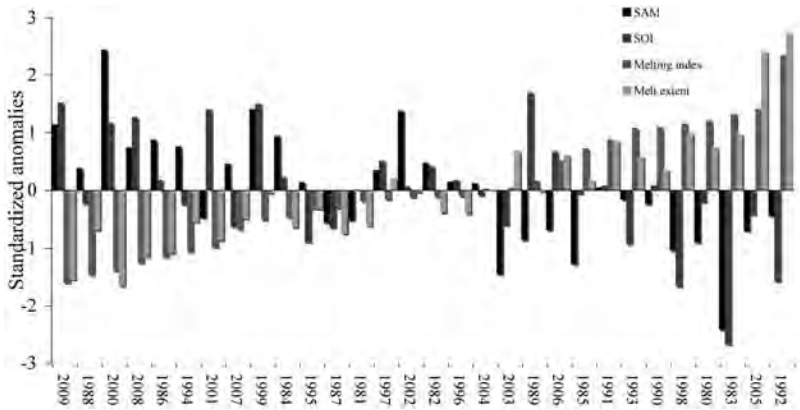

Figure 1. 1980–2009 standardized SAM, SOI, snowmelt index and extent anomalies rank-ordered from lowest to highest melting index years.

additional loss of an important ice bridge in April 2009. Recent findings indicate that the February 2008 event was linked to rift formation associated with ice rises (areas where the ice shelf makes contact with the seabed), and that surface melting did not play a role in the breakup [*Braun et al.*, 2008]. However, previous ice shelf breakups on the Antarctic Peninsula have been linked to surface melting [*Scambos et al.*, 2000, 2003] and basal thinning due to melt at the ocean-ice interface underneath ice shelves [*Shepherd et al.*, 2003]. Thus, it is possible that elevated surface melting during the past decade [*Tedesco*, 2009] may have played a role in preconditioning the Wilkins for breakup.

2.2. Linkages Between Antarctic Snowmelt and High-Latitude and Tropical Climate Variability

[6] The October through January (ONDJ) averaged SAM and SOI indices are reported in Figure 1. We employ the *Marshall* [2003] surface pressure-based SAM index, and the *Troup* [1965] SOI index compiled by the Australian Bureau of Meteorology. The ONDJ months were chosen to be consistent with *Torinesi et al.* [2003], and because they have the strongest relationship between the SAM and the melt indices (Tables 1 and S1 of the auxiliary material).[1] During a positive phase of the SAM, corresponding to especially low surface pressure at high latitudes, lower-than-normal near-surface temperatures occur over most of mainland Antarctica, with the exception being higher-than-normal temperatures along portions of the Antarctic Peninsula [*Thompson and Solomon*, 2002]. ENSO is known to have important, albeit intermittent, impacts on Antarctic climate [*Bromwich et al.*, 2000]. A prominent cyclonic (anticyclonic) circulation anomaly in the Amundsen and Bellingshausen Seas often occurs during positive (negative) phases of the SOI, with subsequent impacts on anomalies of near-surface temperature, sea ice, and precipitation in West Antarctica [*Yuan and Martinson*, 2001; *Bromwich et al.*, 2004]. Additionally, if positive phases of the SAM are coincident with positive phases of the SOI (e.g., La Niña), their overall impact on Antarctic climate (especially in West Antarctica) can be amplified [*Fogt and Bromwich*, 2006; *Stammerjohn et al.*, 2008].

[7] We found that years in which both SAM and SOI indices had strongly positive anomalies (defined as >0.5 standard deviations) had melt indices of 22.1 million km^2 × days (n = 4). Years in which only one of the two indices had strong positive anomalies (and the other index value was <0.0) had melt indices of 30.8 million km^2 × days (n = 4). The difference is weakly statistically significant (p = 0.09) despite the small sample size (n), making it likely that negative melt anomalies (the average is 34.4 million km^2 ×

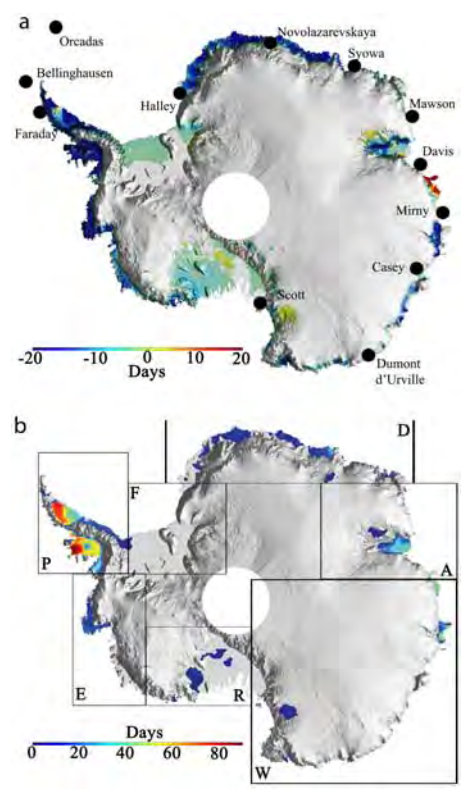

Figure 2. 2009 (a) melting days anomalies and (b) number of melting days. Boxes defining the regions whose results are reported in Table 1 are also shown together with the location of the stations used for our analysis. P, Antarctic Peninsula; F, Filchner-Ronne Ice Shelf; D, Dronning Maud Land; A, Amery Basin; W, Wilkes Land; R, Ross Ice Shelf and Marie Byrd Land; E, Ellsworth Land.

[1]Auxiliary materials are available in the HTML. doi:10.1029/2009GL039186.

Table 1. Correlation Between Snowmelt Index or Extent and SAM, SOI, and SAM+SOI Indices for the Period 1980–2009[a]

	Melting Index			Melt Extent		
	SAM	SOI	SAM+SOI	SAM	SOI	SAM+SOI
Whole	−0.65	−0.59	−0.71	−0.59	−0.57	−0.65
Peninsula	**−0.30**[b]	**−0.28**[c]	−0.33	−0.52	−0.44	−0.54
Filchner[d]	**0.09**	**−0.11**	**−0.01**	**0.1**	**−0.10**	**0.01**
Dronning	−0.54	−0.46	−0.57	−0.46	−0.40	−0.49
Amery	−0.58	−0.44	−0.58	−0.51	−0.51	−0.59
Wilkes	−0.51	−0.39	−0.51	**−0.32**[e]	**−0.29**[f]	**−0.35**[g]
Ross	−0.55	−0.56	−0.63	−0.56	−0.51	−0.61
Ellsworth	−0.57	−0.53	−0.63	−0.57	−0.55	−0.63

[a]Results are statistically significant at 5% level, with the exception of those cases highlighted in bold, with p-values explicitly reported in the following.
[b]0.10.
[c]0.13.
[d]The p-values for the Filchner area are greater than 0.6.
[e]0.12.
[f]0.08.
[g]0.06.

days) are amplified when both the SAM and SOI forcing are strongly positive. Three of the four lowest melt years had strongly positive SAM and SOI forcing as defined here (Figure 1). For the opposite case, there was no statistically significant amplification of positive melt anomalies when both indices had strongly negative anomalies, although both indices had large negative anomalies during several of the highest melt years.

[8] The 2009 extreme negative snowmelt index and extent anomalies are likely related to coincident strong positive phases of both the SAM and SOI during austral spring and summer 2008–2009. The 2008–2009 ONDJ SAM index was +1.14 times the standard deviation above the 1980–2009 mean, being the 4th highest for the 1980–2009 period. The 2008–2009 ONDJ SOI index was the 2nd highest recorded for 1980–2009, being +1.52 times the standard deviation above the mean, indicating La Niña conditions. December 2008 temperature anomalies from the Reference Antarctic Data for Environmental Research (READER) database [*Turner et al.*, 2004] around the coasts of Antarctica were consistent with the typical pattern described above for the SAM, being negative around most of mainland coastal Antarctica and positive along the Peninsula (Figure 3a). Additionally, December 2008 Antarctic-wide sea ice cover was more extensive than for the long-term mean [*Fogt*, 2009], which probably reinforced the overall cooler-than-normal coastal station temperatures. The anticorrelation between coastal surface temperature and snowmelt and the SAM and SOI indices is apparent in Figure 3b, although in some years the melt anomalies are near neutral despite strong forcing from at least one of the indices. For example, in 2002 the SAM anomaly was above 1 standard deviation from the mean, but coastal temperatures and snowmelt anomalies were nearly zero rather than negative. An amplified wave three atmospheric circulation pattern (for which the causality is not well understood) occurred around Antarctica during summer 2001–2002. This led to anomalous winds and enhanced warm air advection from mid-latitudes and reduced sea ice concentrations along much of the coast, especially in the Weddell and Bellingshausen Seas, preceding the breakup of the Larsen B ice shelf in February 2002 [*van den Broeke*, 2005; *Massom et al.*, 2006].

[9] Table 1 shows the values of the correlation (r) between cumulative summer snowmelt index or extent (reported in Figure 2b) and the SAM and SOI indices (and their sum: SAM+SOI) for the period 1980–2009 for the whole continent and for the regions outlined in Figure 2b. Despite differences among melting indices and extent derived from various remote sensing algorithms [*Tedesco*, 2009], we found that the variability and trends of standardized cumulative annual snowmelt index and extent values from the different methods agree within a few percent and therefore the results are not dependent on the choice of algorithm. Statistically significant anti-correlations generally occur for both snowmelt index and extent. At the continent scale the indices explain 42% (SAM) and 35% (SOI) of the inter-annual melting index variability and 34% (SAM) and 33% (SOI) of the melt extent variability. The anti-correlation between snowmelt and the SAM index is stronger than with the SOI index for nearly all regions, consistent with studies indicating that SAM is the principal driver of Antarctic near-surface temperature variability [e.g., *Marshall*, 2007]. The strongest anti-correlations are obtained when considering the sum of the SAM and SOI indices, explaining, respectively, 50% (42%) of the melt index (extent) variability. Although the sum is a simplistic proxy of the nonlinear interaction between the two indices [*Fogt and Bromwich*, 2006], it reflects the amplification effect described above when both indices are in strong positive phases.

[10] Weak correlations occur in some regions: the correlations between the SAM and SOI and snowmelt indices over the Peninsula are not statistically significant, and the same is true in the Wilkes area for snowmelt extent. Low correlation values on the Peninsula may be partially attributed to strong local forcing due to the substantial decreases in sea ice duration in recent years on the west side of the Peninsula that are partly related to the SAM and ENSO [e.g., *Stammerjohn et al.*, 2008], but also may be linked to regional ocean warming for which the causality is not well known [*Payne et al.*, 2004]. The especially weak correlations between the SAM and SOI and snowmelt indices in the Filchner region may be related to the cyclonic circulation anomaly that often occurs off the coast of West Antarctica during positive phases of the SOI, causing enhanced warm air advection onto the Ronne-Filchner ice shelf [*Yuan and Martinson*, 2001; *Bromwich et al.*, 2004] which is favorable for greater melt. Conversely, positive SAM forcing is favorable for cooler temperatures [*Marshall*, 2007]. Because the ONDJ SAM and SOI are positively correlated (r = 0.55, 1980–2009), there may be a limited regional cancelling effect when the two indices occur in phase (Figure S1b).

3. Conclusions

[11] Negative melting anomalies observed in recent years do not contradict recently published results on surface temperature trends over Antarctica [e.g., *Steig et al.*, 2009]. The time period used for those studies extends back to the 1950's, well beyond 1980, and the largest temperature

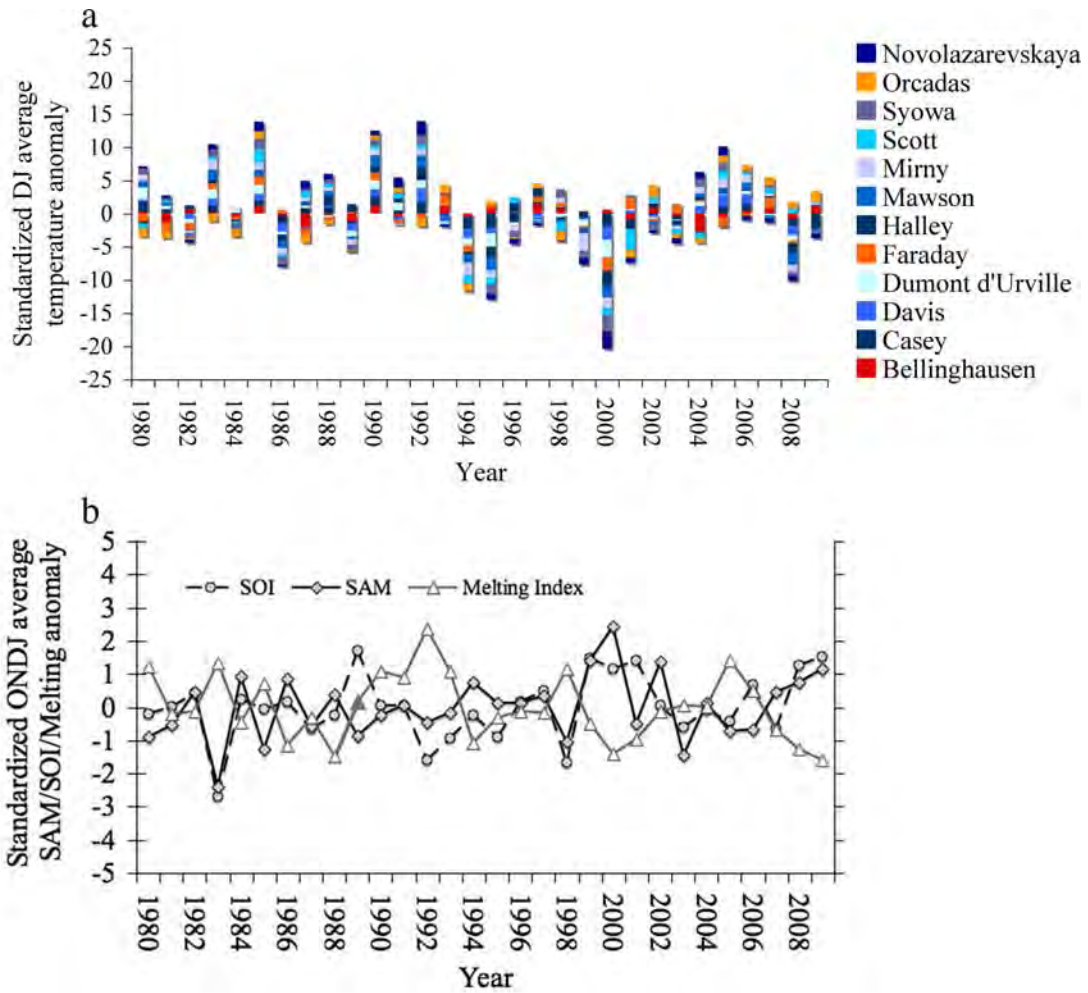

Figure 3. (a) Standardized cumulative December–January monthly averaged surface temperature anomaly for the stations mapped in Figure 2 (i.e., the standardized temperature anomalies are plotted on top of each other); (b) ONDJ SOI (thick dashed line with circles), SAM (thick solid line with diamonds), and standardized snowmelt index anomalies (thin solid line with triangles).

increases are found during winter and spring rather than summer, and are generally limited to West Antarctica and the Antarctic Peninsula. Summer SAM trends have increased since the 1970s [*Marshall*, 2003], suppressing warming over much of Antarctica during the satellite melt record [*Turner et al.*, 2005]. Moreover, melting and surface temperature are not necessarily linearly related because the entire surface energy balance must be considered [*Liston and Winther*, 2005; *Torinesi et al.*, 2003].

[12] Increasing summer SAM trends during recent decades have been linked to stratospheric ozone depletion during austral spring [e.g., *Arblaster and Meehl*, 2006]. Climate model simulations suggest that the summer SAM trends may subside during the 21st century if stratospheric ozone levels recover as projected, with important effects on the atmospheric circulation around Antarctica [*Shindell and Schmidt*, 2004; *Perlwitz et al.*, 2008]. Our results suggest that enhanced summer melting is likely to occur if the positive SAM trends subside. Efforts to elucidate the roles of all of the natural and anthropogenic mechanisms that influence SAM and ENSO variability will be important steps toward projecting future melt in Antarctica, and subsequent impacts on ice sheet mass balance and sea level.

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