AGU PUBLICATIONS

Geophysical Research Letters

RESEARCH LETTER

10.1002/2015GL065750

Key Points:
- Dramatic twentieth century increase in snowfall in West Antarctica
- Snowfall driven by tropical sea surface temperatures and large-scale atmospheric circulation
- Evidence that predicted anthropogenically forced deepening of the Amundsen Sea Low is already happening

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Citation:
Thomas, E. R., J. S. Hosking, R. R. Tuckwell, R. A. Warren, and E. C. Ludlow (2015), Twentieth century increase in snowfall in coastal West Antarctica, *Geophys. Res. Lett.*, *42*, 9387–9393, doi:10.1002/2015GL065750.

Received 10 AUG 2015
Accepted 21 SEP 2015
Published online 3 NOV 2015

Twentieth century increase in snowfall in coastal West Antarctica

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Abstract The Amundsen Sea sector of the West Antarctic ice sheet has been losing mass in recent decades; however, long records of snow accumulation are needed to place the recent changes in context. Here we present 300 year records of snow accumulation from two ice cores drilled in Ellsworth Land, West Antarctica. The records show a dramatic increase in snow accumulation during the twentieth century, linked to a deepening of the Amundsen Sea Low (ASL), tropical sea surface temperatures, and large-scale atmospheric circulation. The observed increase in snow accumulation and interannual variability during the late twentieth century is unprecedented in the context of the past 300 years and evidence that the recent deepening of the ASL is part of a longer trend.

1. Introduction

Extensive thinning of fast flowing glaciers [*Pritchard et al.*, 2009] has made the Amundsen coast region one of the largest Antarctic contributors to sea level rise [*Shepherd et al.*, 2012]. Calculating Antarctic mass balance and its potential contribution to sea level rise is dependent on a good understanding of spatial and temporal changes in Antarctic snow accumulation, the net result of precipitation, sublimation, snow drift, and melt. Snow accumulation is a difficult parameter to measure and is largely based on remote sensing and atmospheric modeling. Despite a reported insignificant change in total Antarctic snow accumulation since the 1950s (1957–2004) [*Monaghan et al.,* 2006], regionally there are significant trends. In the Antarctic Peninsula models reveal an upward trend in regional precipitation since 1979 [*Lenaerts et al.*, 2012; *van den Broeke et al.*, 2006], an increase in elevation (1992–2003) [*Davis et al.*, 2005], and an increase in ice core derived snow accumulation [*Thomas et al.*, 2008]. Conversely, in West Antarctica no trend in either measured or modeled snow accumulation is observed between 1980 and 2009 on Thwaites Glacier [*Medley et al.,* 2013], while in central West Antarctica observed and simulated records show a negative trend in accumulation rates during this period [*Burgener et al.*, 2013].

An area where snow accumulation is not well constrained is the Bellingshausen-Amundsen coast region between the Antarctic Peninsula and West Antarctica. The Amundsen coast has been losing mass in recent decades [*Pritchard et al.*, 2009; *Shepherd et al.*, 2012], as a result of ocean-driven basal melt and Southern Hemisphere wind patterns [*Pritchard et al.*, 2012]. Changes in annual snow accumulation are still important for ice sheets mass balance, with recent studies showing that an increase in snow accumulation over Antarctica will result in additional dynamic ice loss [*Winkelmann et al.*, 2012]. It is expected that the observed recent atmospheric warming in this region [*Bromwich et al.*, 2013] will result in increased snow accumulation, although the stable water isotopes from Ellsworth Land ice cores have shown that the recent rise in temperature here is not unusual in the past 300 years [*Thomas et al.*, 2013]. Therefore, it is unclear whether these recent glaciological changes are part of a longer term natural trend or associated with anthropogenic climate forcing. Here we use two ice core snow accumulation records from coastal Ellsworth Land (Ferrigno and Bryan Coast (Figure 1)) to assess the significance of the recent trends in the context of the past 300 years.

2. Methods and Data

Snow accumulation data are presented from two ice cores drilled on the Bryan Coast, West Antarctica during the austral summer 2010/2011. The 136 m Ferrigno ice core was drilled on a three-way ice divide between the Ferrigno glacier and Pine Island glacier (74°34′37S, 86°54′16W, 1350 m above sea level (asl)) in December 2010. The 140 m Bryan Coast ice core was drilled on the ice divide 136 km west of the

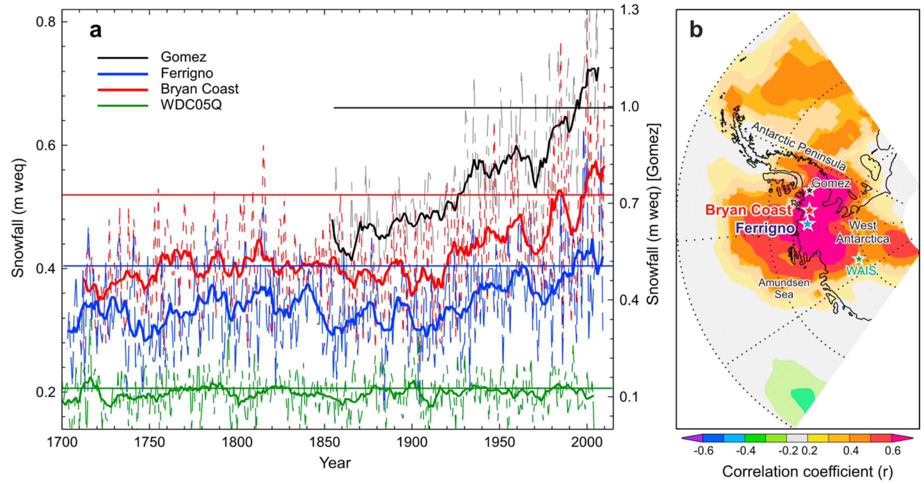

Figure 1. (a) Annual average snow accumulation (thin lines) and running decadal means (thick lines) for Gomez [*Thomas et al.*, 2008], Bryan Coast (red), Ferrigno (blue), and WAIS divide WDC05Q [*Banta et al.*, 2008] (green). Solid horizontal lines indicate the average for each record in the period 1980–2010. (b) Spatial correlation plot of Bryan Coast snow accumulation and precipitation—evaporation from ERA-Interim 1979–2010 [*Dee et al.*, 2011]. Stars indicate ice core locations, and brighter coloring indicates $p < 0.05$.

Ferrigno site (74°29′46S, 81°40′41W, 1177 m asl) in January 2011. The ice depth is 1320 + 5 m at Ferrigno, estimated using the British Antarctic Survey (DEep-LOok Radar Echo Sounder) system, and 1100 ± 5 m at Bryan Coast.

The snow accumulation record from all ice cores was derived using the summer maxima in nonsea-salt sulfate, measured with ion chromatography using a reagent-free Dionex ICS-2500 anion and IC 2000 cation system. Samples were measured at 5 cm resolution, corresponding to approximately eight samples per year. Snow accumulation is converted to meters of water equivalent (mweq) based on the density profile and corrected for thinning using the Nye model [*Nye*, 1963], which assumes a vertical strain rate and an ice sheet that is frozen to the bed, suitable for the upper 10–15% of the ice sheet.

The meteorological data come from the European Centre for Medium-range Weather Forecasts (ECMWF) Re-Analysis-Interim analysis (1979–2010) [*Dee et al.*, 2011]. It updates the previous ERA-40 reanalysis, with improved model physics and observational data supplemented by ECMWF's operational archives, providing a better representation of the hydrological cycle in the high Southern Hemisphere latitudes than earlier reanalyses [*Bromwich et al.*, 2011; *Bracegirdle and Marshall*, 2012]. It correlates with ice core accumulation records from the southern Antarctic Peninsula (Gomez) [*Thomas and Bracegirdle*, 2009] and captures subannual accumulation variability at the Ferrigno site [*Thomas and Bracegirdle*, 2015]. The ice core snow accumulation (the sum of precipitation, ablation, and windblown deposition) at both sites is significantly correlated with annual precipitation-evaporation (P-E) from ERA-Interim (1979–2010) (Figure 1b, the Ferrigno spatial correlation is not shown but is almost identical to Bryan Coast), demonstrating that the records are capturing precipitation variability at each site.

Meridional winds and SLP (1871–2010) have been used from the NOAA CIRES twentieth century reanalysis data (20CR) [*Compo et al.*, 2011], an ensemble of 56 atmospheric general circulation models. SST's are from the extended reconstructed sea surface temperature (ERSST version 3b) [*Smith et al.*, 2008]. All correlations presented in this study are carried out using detrended data with the significance levels for Pearson's correlation calculated using the two-tailed *t* test.

3. Results and Discussion

3.1. Twentieth Century Trends

Prior to 1900 the annual average snow accumulation at Ferrigno and Bryan Coast remained fairly constant at 33 cm yr^{-1} and 40 cm yr^{-1}, while after 1900 the snow accumulation increased at a rate of 0.13 cm yr^{-1} and 0.15 cm yr^{-1}, respectively. Snow accumulation during the most recent decade (2000–2009) is 27% higher

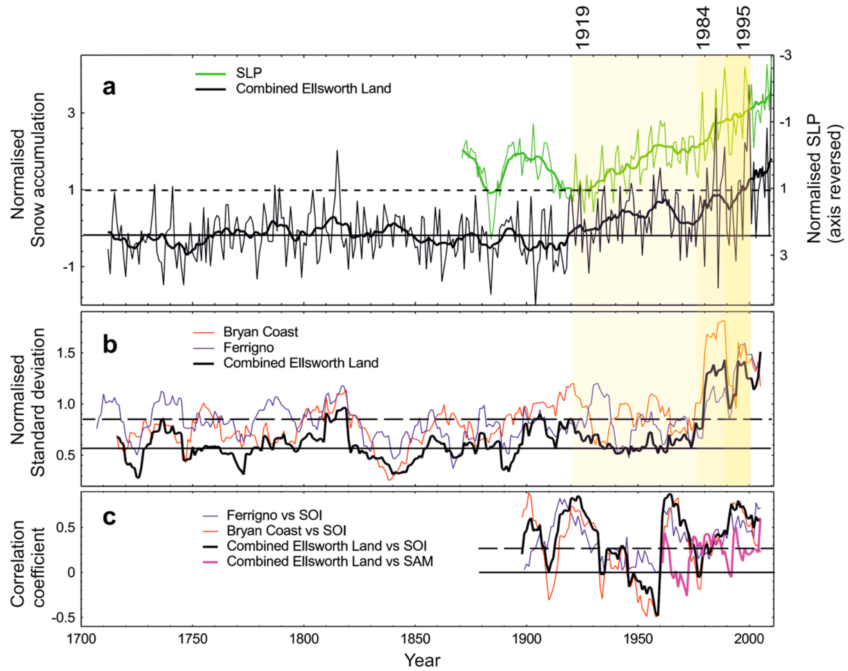

Figure 2. (a) Normalized combined Ellsworth Land snow accumulation record and SLP (green) from 20CR in the ASL region (defined as 170–290°E, 60–75°S) as annual average (thin lines) and running decadal means (thick lines). (b) Running decadal standard deviation from the normalized Ferrigno (blue), Bryan Coast (red), and combined Ellsworth Land snow accumulation record. Horizontal solid lines represent baseline averages (1712–1899) and dashed lines $+2\sigma$ above the baseline average. Shading and dates highlight key transitions referred to in the text. (c) Running decadal correlations between the SOI and snow accumulation at Ferrigno (blue), Bryan Coast (red), and combined Ellsworth Land record (black) and correlation between SAM and combined Ellsworth Land record (pink). Horizontal dashed line indicates significance at $p < 0.01$.

at Ferrigno and 31% higher at Bryan coast than the baseline values determined from 1712 to 1899. This twentieth century increase is consistent with the Gomez ice core record from the southwestern Antarctic Peninsula (Figure 1a (black)) which revealed a doubling of snow accumulation since 1854 with an increasing trend that began in the ~1930s and accelerated in the mid-1970s [*Thomas et al.*, 2008]. Determining the onset of the trend is heavily dependent on the statistical approach used; however, the Ellsworth Land ice cores appear to corroborate the onset of this snow accumulation increase. There is significant correlation between the two Ellsworth Land records and the Gomez record from the southern Antarctic Peninsula ($r^2 > 0.75$, decadal), suggesting that these records are capturing local and regional (>350 km longitudinally) accumulation variability. Spatially averaging the records together reduces the amount of small-scale noise, resulting from local wind redistribution and sublimation. Thus, a combined Ellsworth Land record was produced by averaging the normalized Ferrigno and Bryan Coast records (1712–2010), and a regional Ellsworth Land record was produced in the same way but includes the Gomez record (1854–2006). Using the combined Ellsworth Land record and selecting the period 1712–1899 as the baseline, we observe that after 1919 the running decadal mean exceeds the baseline average (Figure 2a) and remains above it for the remainder of the twentieth century. The increase in snow accumulation accelerates in recent decades with the running decadal mean since 1995 consistently exceeding two standard deviations (2σ) above the baseline average. Looking at the individual records, the increase at Ferrigno is less pronounced with 8 of the last 30 years exceeding 2σ above baseline average compared to 13 of the last 30 years at Bryan Coast. This is in contrast to the insignificant trend observed at WAIS divide (WDC05Q) ice core (Figure 1a (green)) [*Banta et al.*, 2008], and the negative trends observed from the Satellite Era Accumulation Traverse (SEAT 2010) ice cores from central West Antarctica [*Burgener et al.*, 2013], suggesting that the observed twentieth century increase is confined to the Antarctic Peninsula and Ellsworth Land, with the magnitude decreasing from east (Gomez) to west (Ferrigno).

3.1.1. Twentieth Century Variability

The temporal variability is examined using running decadal standard deviations for the combined Ellsworth Land snow accumulation record (Figure 2b) revealing an abrupt increase after 1984, when values are more

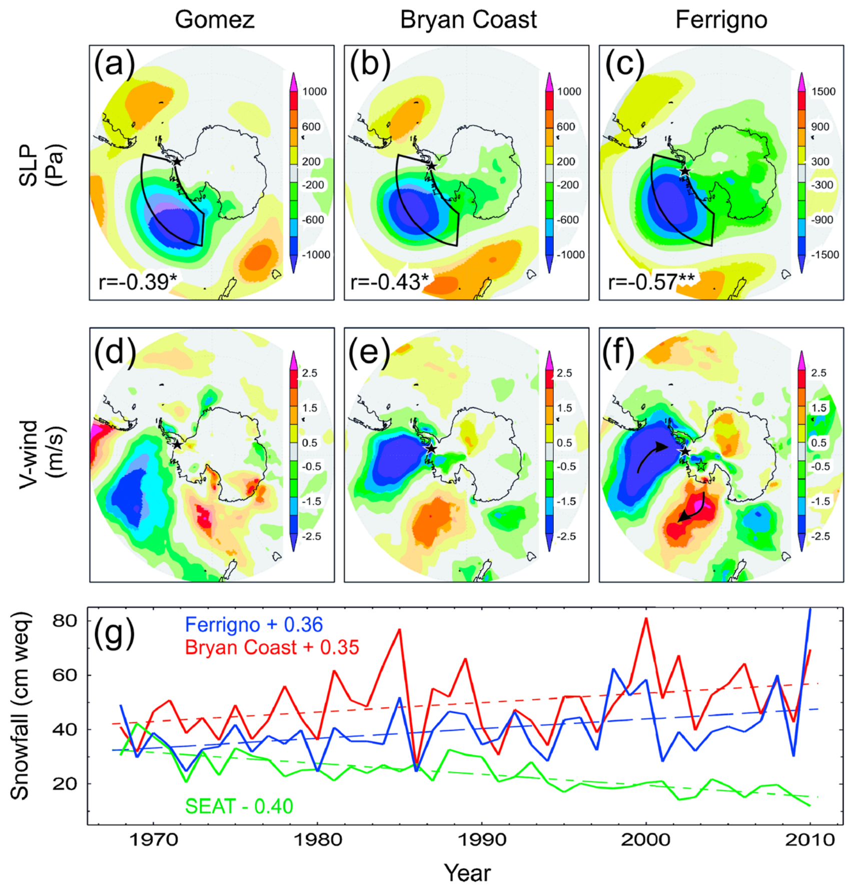

Figure 3. Regression plots of annual average snow accumulation from Gomez [*Thomas et al.*, 2008], Bryan Coast, and Ferrigno with annual average (a–c) SLP and meridional (d–f) V winds from ERA-Interim 1979–2009 [*Dee et al.*, 2011] with correlation coefficients (*$p < 0.10$ and **$p < 0.05$) with SLP in ASL region (highlighted box (Figures 3a–3c)) shown for each record. Brighter coloring indicates $p < 0.05$, and black stars indicate ice core locations (note the different axis in Figure 3c). Green star indicates location of SEAT 2010 record with arrows (Figure 3f) representing the simplified clockwise rotation of the ASL. (g) Annual snow accumulation (cm weq) at Bryan Coast (red), Ferrigno (blue), and stacked SEAT 2010 record [*Burgener et al.*, 2013] (green) with trends shown (1968–2010).

than double the average for the previous ~270 years. This jump coincides with the observed shift in interdecadal temperature variability observed a Byrd Station in West Antarctica, especially during the austral summer and winter [*Bromwich et al.*, 2013].

3.2. Climate Drivers

Spatial regression plots of annual average ice core snow accumulation with sea level pressure (SLP) and meridional wind (v10) from ERA-Interim (Figure 3) reveal that the dominant feature governing precipitation variability at the Ellsworth Land and the Gomez sites is the climatological low pressure system that extends across the Amundsen and Ross Seas. This is a region of high synoptic activity and the largest contributor of the total Antarctic meridional moisture flux [*Tsukernik and Lynch*, 2013], with the highest interannual and seasonal variability. This persistent deep low-pressure system, the result of the frequency and intensity of individual cyclones, is referred to as the Amundsen Sea Low [*Baines and Fraedrich*, 1989; *Turner et al.*, 2013], the location and central pressure of which affects the climatic conditions on the Antarctic Peninsula and West Antarctica.

ERA-Interim SLP (1979–2010) from the ASL region (defined 170–290°E, 60–75°S) exhibits a deepening trend [*Hosking et al.*, 2013] and is negatively correlated with snow accumulation at all sites (Figure 3). The strongest relationship is observed at Ferrigno and the weakest at Gomez, the most eastern site. At all sites high snow accumulation years are associated with a reduction in regional pressure in the vicinity of the ASL, leading to strengthened circumpolar westerlies and enhanced northerly flow (Figures 3d–3f) with back trajectory analysis, revealing that over half of all air masses reaching Ellsworth Land originate in the south Pacific sector of the Southern Ocean, but anomalous high snow accumulation years occur when transport is confined to this region [*Thomas and Bracegirdle*, 2015]. Winds in this region directly impact global sea level rise through ocean-driven basal melt, resulting in widespread ice shelf thinning on the coast of West Antarctica [*Pritchard et al.*, 2012]. The onshore winds to the east of the ASL are potentially poorly represented within the CMIP5 climate models due to the smoothed low-lying representation of the Antarctic Peninsula which in the real-world acts as a barrier to direct flow toward Ellsworth Land. The mechanism of lower SLP in the Amundsen Sea sector creates a dipole pattern of enhanced precipitation in Ellsworth Land and reduced precipitation over West Antarctica, reflecting the clockwise rotation of air masses and moisture advection paths around the ASL (Figure 3f). Comparison with the SEAT 2010 [*Burgener et al.*, 2013] records reveal a negative trend in West Antarctic snow accumulation, equivalent to the positive trends (1968–2010) observed in the Ellsworth Land cores (Figure 3g). Assuming 20CR has some skill in reconstructing SLP, then the relationship between snow accumulation and SLP in this region appears to be stable beyond the instrumental period (Figure 2a), [*Compo et al.*, 2011] (1871–2010). However, it is difficult to assess the reliability of the 20CR for the southern ocean and Antarctica, which reportedly contains nonclimatic inhomogeneities [*Ferguson and Villarini*, 2014].

The transient eddy coastal flux in the Amundsen Sea region, the main driver for atmospheric moisture flux, exhibits a decreasing trend since 1979 [*Tsukernik and Lynch*, 2013] in contrast to the increased accumulation observed in the ice core records. Another possible driver for increased snow accumulation at these sites could be the observed reduction in sea ice in the Amundsen Sea resulting in enhanced availability of surface level moisture and increased poleward atmospheric moisture transport [*Tsukernik and Lynch*, 2013]. This could explain the longitudinal differences between the ice core sites, with the least significant changes in accumulation in the west (Ferrigno) and the greatest changes observed in the eastern sites (Gomez), where adjacent sea ice exhibits the largest decreasing trend [*Turner et al.,* 2009]. However, the role of surface level moisture in the total moisture flux and the mechanisms behind the decreasing trends in transient eddy flux remain unclear.

3.2.1. Modes of Climate Variability

Pressure in the ASL region is strongly modulated by large-scale modes of climate variability such as the Southern Annular Mode [*Dee et al.*, 2011] and the El Niño Southern Oscillation (ENSO) [*Fogt et al.*, 2012; *Hosking et al.*, 2013]. The Southern Annular Mode (SAM) describes the strength of the middle- to high-latitude meridional pressure gradient and was found to be a primary factor governing decadal variability of accumulation at the Gomez site [*Thomas et al.*, 2008]. Studies using regional climate models have linked the increasing accumulation around the Antarctic coast to the positive phase of the SAM [*Dethloff et al.*, 2010]. Using an observation-based annual SAM index, available from 1957 onward [*Marshall*, 2003], reveals significant correlations with the snow accumulation at Ferrigno; however, the relationship at both Ferrigno and Bryan Coast is not temporally stable. Running decadal correlations (not shown) reveal significant correlations between SAM and Ferrigno snow accumulation since 1988, while the correlation between SAM and the combined Ellsworth Land snow accumulation record (Figure 2c) is weak during the whole period (1957–2010).

Tropical sea surface temperature (SST) anomalies significantly influence atmospheric circulation in the Amundsen Sea region through the generation of a large-scale atmospheric wave train [*Ding et al.*, 2011; *Lachlan-Cope and Connolley*, 2006]. Spatial correlations of the regional Ellsworth Land snow accumulation record (includes Gomez) with SSTs [*Smith et al.*, 2008] since 1980 (Figure 4a) reveal a strong negative ENSO-like pattern however the pattern is diminished when extending the correlations back to 1854 (Figure 4b). This is corroborated by the temporal instability between snow accumulation and the Southern Oscillation Index (SOI) (1882–2010), a commonly employed measure of the strength and phase of ENSO, as observed at Gomez [*Thomas et al.*, 2008] and demonstrated in GCM experiments [*Lachlan-Cope and Connolley*, 2006]. Running decadal correlations of snow accumulation with the SOI reveals not only positive correlations since the 1980s but also periods of insignificant and even negative correlations during the twentieth century (Figure 2c). It has been suggested that ENSO's influence across West Antarctica and the Antarctic Peninsula is tied to the strength and phase of the SAM [*Clem and Fogt,* 2013] and may explain the acceleration in the snow accumulation trend since the 1990s, when both SAM and ENSO are in-phase. However, examination of the meridional moisture transport in the Amundsen Sea sector, based on ERA-Interim (1979–2010), concluded that the moisture flux variability cannot be explained by either SAM or ENSO, even in the pacific sector [*Tsukernik and Lynch*, 2013].

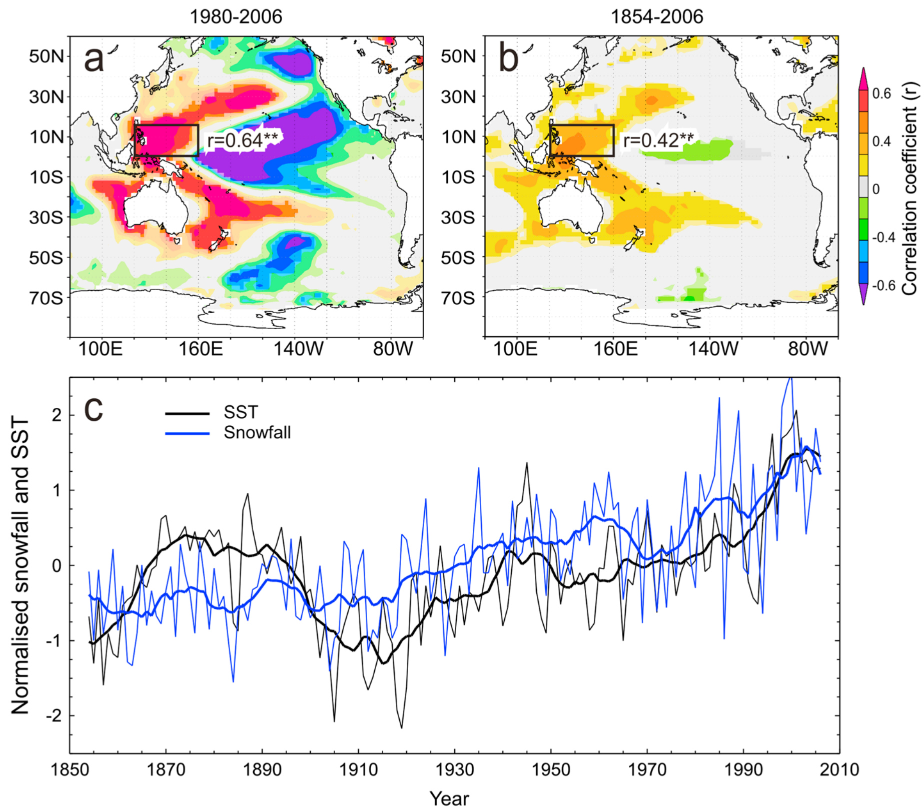

Figure 4. Spatial correlation plots of annual average SSTs (from ERSST.v3b) [*Smith et al.*, 2008] with the normalized Ellsworth Land snow accumulation record from (a) 1980–2006 and (b) 1900–2006. Brighter coloring indicates $p < 0.05$, black box highlights the area averaged SST plotted in Figure 4c with the corresponding correlation coefficients (*$p < 0.10$, **$p < 0.05$). (c) Normalized regional Ellsworth Land snow accumulation record (blue) and West Pacific SSTs (black, 0–15°S, 120–160°E) as annual average (thin lines) and running decadal means (thick lines).

The spatial correlations between snow accumulation and SSTs in the western Pacific, not associated with ENSO, is maintained ($r = 0.46$, $p < 0.05$) back to 1854. However, the absence of negative anomalies in the eastern Pacific may be an artifact of SST errors in the reconstruction which are hard to assess in this data sparse region. The area averaged SST record from the West Pacific (black box Figure 4) reveals a twentieth century warming that accelerated since the 1990s, with coincident SST cooling and reduced snow accumulation events during the early 1970s and late 1980s, suggesting changes in the tropical Pacific not directly related to ENSO are driving high-latitude circulation as observed in other studies [*Ding et al.*, 2011; *Thomas et al.*, 2013].

4. Conclusions

Ice core records from Ellsworth Land, West Antarctica reveal a twentieth century increase in regional snow accumulation and its interannual variability that is considered exceptional in the context of the past 300 years. The annual snow accumulation since 1900 increased by ~ 30%, proving that the dramatic increases observed in the Antarctic Peninsula extend into West Antarctica and that these changes occurred following a 200 year period of relatively stable conditions. Snow accumulation in this region is governed by changes in SLP in the Amundsen Sea region, resulting in enhanced meridional (onshore) winds drawing moist air to the coast of Ellsworth Land, and directly impacting global sea level rise through wind driven upwelling and subsequent thinning of West Antarctic ice shelves [*Pritchard et al.*, 2012]. The close relationship between SLP and snow accumulation at these sites make this a unique proxy for past ASL (and onshore wind) conditions. The recent deepening trend of the ASL is predicted to continue through the 21st century in response to greenhouse gas concentration increases [*Raphael et al.*, 2015]. The dramatic increase in snow accumulation in Ellsworth Land provides evidence that this recent deepening in the ASL region is part of a longer trend, observed as early as the 1920s, with acceleration since the 1990s when the coupling between ENSO and SAM is strongest.

Acknowledgments
This work was funded by the British Antarctic Survey and part funded by the Natural Environment Research Council (grant NE/J020710/1). We would like to thank P. Anker for the drilling assistance, S. Rupper for providing the SEAT 2010 data, and two anonymous reviewers for their valuable suggestions. The data can be downloaded at the World Data Center (WDC) for Paleoclimatology (www.ncdc.noaa.gov).

The Editor thanks David Bromwich and an anonymous reviewer for their assistance in evaluating this paper.

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