AGU PUBLICATIONS

Geophysical Research Letters

RESEARCH LETTER
10.1002/2017GL075135

Snow Accumulation Variability Over the West Antarctic Ice Sheet Since 1900: A Comparison of Ice Core Records With ERA-20C Reanalysis

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Key Points:
- ERA-20C has the skill for simulating the interannual variability in snow accumulation over West Antarctica since 1900
- Contrasting patterns in West Antarctic regional snow accumulation change between 1900 and 2010
- Snow accumulation variability broadly related to sea level pressure and sea ice changes in the Amundsen Sea Low sector

Supporting Information:
- Supporting Information S1
- Table S1

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Citation:
Wang, Y., Thomas, E. R., Hou, S., Huai, B., Wu, S., Sun, W., … Zhang, Y. (2017). Snow accumulation variability over the West Antarctic Ice Sheet since 1900: A comparison of ice core records with ERA-20C reanalysis. *Geophysical Research Letters*, *44*, 11,482–11,490. https://doi.org/10.1002/2017GL075135

Received 1 AUG 2017
Accepted 6 NOV 2017
Accepted article online 9 NOV 2017
Published online 23 NOV 2017

Abstract This study uses a set of 37 firn core records over the West Antarctic Ice Sheet (WAIS) to test the performance of the twentieth century from the European Centre for Medium-Range Weather Forecasts (ERA-20C) reanalysis for snow accumulation and quantify temporal variability in snow accumulation since 1900. The firn cores are allocated to four geographical areas demarcated by drainage divides (i.e., Antarctic Peninsula (AP), western WAIS, central WAIS, and eastern WAIS) to calculate stacked records of regional snow accumulation. Our results show that the interannual variability in ERA-20C precipitation minus evaporation (P − E) agrees well with the corresponding ice core snow accumulation composites in each of the four geographical regions, suggesting its skill for simulating snow accumulation changes before the modern satellite era (pre-1979). Snow accumulation experiences significantly positive trends for the AP and eastern WAIS, a negative trend for the western WAIS, and no significant trend for the central WAIS from 1900 to 2010. The contrasting trends are associated with changes in the large-scale moisture transport driven by a deepening of the low-pressure systems and anomalies of sea ice in the Amundsen Sea Low region.

1. Introduction

The West Antarctic Ice Sheet (WAIS) is of great scientific and societal interest because it plays a key role in global sea level changes and atmospheric circulation as it has been rapidly warming since the 1950s (Bromwich et al., 2013). The extensive discharge of outlet glaciers on the Antarctic Peninsula (AP) and in the Amundsen Sea sector accounts for the majority of the Antarctic contribution to global sea level rise in recent decades (e.g., Mouginot et al., 2014; Rignot & Mouginot, 2014; Wouters et al., 2015). Snow accumulation is the largest input for the ice sheet mass balance, balancing the loss from ice discharge. Therefore, its changes have significant implications for the global sea level. For example, Winkelmann et al. (2012) have suggested that the additional weight from increased snow accumulation may lead to increase in the ice discharge into the ocean on centennial and longer time scales. Thus, establishing an accurate history of snow accumulation is essential for understanding not only variability in the WAIS mass balance and its sensitivity to climate forcing but also its long-term implications for the global sea level.

Great efforts have been made to directly measure snow accumulation over the WAIS by means of snow pits, ice/firn cores, stake or stake farms, ground-penetrating radar, and remote sensing techniques (Eisen et al., 2008). However, the temporal variability of West Antarctic snow accumulation is still not well known due to the considerable challenges faced by each method. Stake measurements are local and often cover a too short time span. Remote sensing techniques can overcome the spatial sparseness of in situ observations but also suffer from short temporal coverage. By comparison, firn/ice cores provide a long-term record of snow accumulation and its temporal variability, but they are usually too spatially sparse. In particular, the large-scale signals of snow accumulation variability in a single core may be obscured by postdepositional noises, e.g., sublimation and redistribution by snowdrift. Averaging multiple cores from a given region can, to a great extent, compensate for local disturbance of small-scale variability at individual ice core sites.

An ever growing number of national and international expeditions have greatly increased the coverage of ice core records over West Antarctica, revealing regional differences in the snow accumulation variability. Thomas et al. (2008) have found a doubling of snow accumulation since 1850 in the AP, while coastal ice cores from the eastern WAIS reveal a 30% increase in annual snow accumulation since 1900 (Thomas et al., 2015). Based on 13 annually resolved ice core records, Kaspari et al. (2004) have also observed increased accumulation rates since 1970 in the western sector of the Pine Island-Thwaites drainage system. However, no significant trends exist in snow accumulation from 1980 to 2009 on Thwaites Glacier (Medley et al., 2013). During the same period, decreasing snow accumulation rates are observed in the ice cores drilled along the route from WAIS Divide Camp to Amundsen Sea (Burgener et al., 2013). Although these records show the potential zones of snow accumulation variability (increase, insignificant change, and decrease), they cannot provide the total spatial extent of these heterogeneous changes. Therefore, there is still a need to aggregate more observations and climate model outputs to further explore the spatial heterogeneity in the WAIS snow accumulation variability.

Regional climate models and global reanalyses can provide important information on snow accumulation variability and its response to atmospheric circulation variability. However, the published gridded WAIS snow accumulation simulations at high resolution mainly focus on the modern satellite era (post-1979), which restricts the study of the decadal- to multidecadal-scale variations and relationships. Furthermore, these models need to be validated before their application for climate change assessment. Recently, several reanalysis products have extended reanalyses throughout the twentieth century. This extension provides the possibility to shed light on west Antarctic climatic changes at decadal to multidecadal time scales but is dependent on their skills over the WAIS.

The objective of this study is threefold: (1) to evaluate a pilot reanalysis of the twentieth century from the European Centre for Medium-Range Weather Forecasts (ERA-20C) for its skills in simulating regional snow accumulation, (2) to examine the spatial heterogeneity in snow accumulation changes between 1900 and 2010 based on the establishment of the snow accumulation history at the four WAIS subregions demarcated by drainage divides using ice core records from the Antarctic 2k database, and (3) to investigate the drivers of the regional snow accumulation variability.

2. Data and Methods

Annually resolved snow accumulation data from Antarctic ice cores are available at Antarctica 2k database (http://www.pagesigbp.org/ini/wg/antarctica2k/data). The data set were constructed through a rigorous quality control criteria to ensure the reliability of individual record, and each record is also corrected for layer thinning from ice flow and snow densification. In this study, we use snow accumulation data from 32 cores in this data set, and additional five ice core records near the WAIS ice divide collected by the Satellite Era Accumulation Traverse team (Burgener et al., 2013). The core locations are shown in Figure 1a, and detailed information on individual ice cores is summarized in Table S1 in the supporting information.

Monthly gridded meteorological data are obtained from European Reanalysis Interim (ERA-interim) (1979–2010) (Dee et al., 2011) and the twentieth century reanalysis (ERA-20C; 1900–2010) (Poli et al., 2016) by the European Centre for Medium-Range Weather Forecasts. ERA-interim data are used to evaluate spatial representativeness of ice core snow accumulation composites and the quality of sea level pressure (SLP) in ERA-20C during the period of 1979–2010. The monthly precipitation minus evaporation ($P - E$) from ERA-20C are averaged over calendar years for 1900–2010 to compare with the ice core snow accumulation composites. Sea surface temperature (SST) data have been obtained from the 2° × 2° NOAA's Extended Reconstructed SST version 4 (ERSST.v4) (Smith & Reynolds, 2003), which is based on both in situ and satellite measurements and statistical methods to enhance spatial completeness (Huang et al., 2014, 2015). Sea ice concentration data are collected from the Hadley Centre Sea Ice and Sea Surface Temperature data set (HadISST.2.2.0.0) (Titchner & Rayner, 2014).

Individual ice cores not only provide valuable information on regional snow accumulation but also suffer from small-scale perturbation such as wind-driven snow deposition/erosion and relative surface roughness. In order to mitigate such local effects, the ice cores are divided into four geographic subgroups: the Antarctic Peninsula (AP), eastern WAIS, central WAIS, and western WAIS drainage basins defined by Rignot et al. (2013). Each core record is standardized as the anomaly from its average for 1961–1990 divided by the standard deviation of the same period. The standardized records in each group are then averaged to form a composite record. The correlation coefficients are calculated based on linearly detrended data, and the two-tailed t test are used to calculate the significance levels for Pearson's correlation.

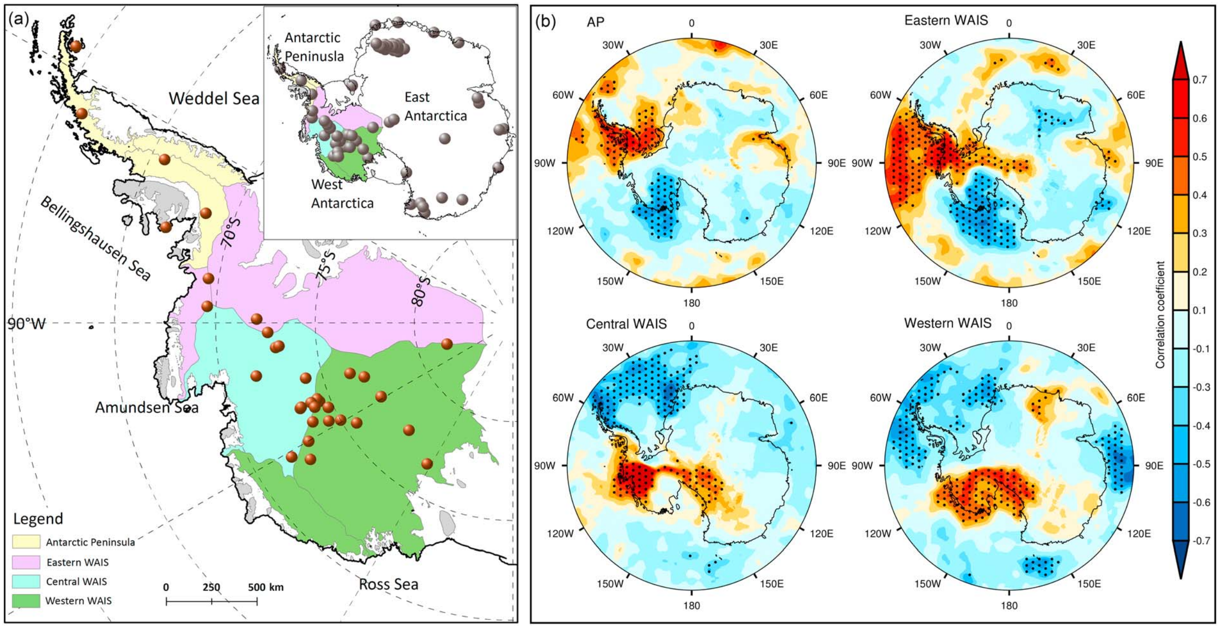

Figure 1. (a) Ice core drilling locations over the WAIS and the four subregional boundaries used in this study. (b) Spatial correlation between regional snow accumulation composites and P − E from ERA-interim (1979–2010). Grid points at the 95% confidence level are dotted.

3. Results and Discussion

3.1. A Comparison Between Ice Core Composites and ERA-20C Simulations

Changes in snow accumulation at a given site may differ from the regional average as a result of highly variable surface slopes and curvature and postdepositional processes. A composite record could mitigate such local disturbance and maintain regional signals. We fist evaluate the regional representativeness of each composite record by comparing it with the ERA-interim P − E data (1979–2010), as it is considered the most reliable for Antarctic precipitation interannual variability among the current reanalysis products (Bromwich et al., 2011; Wang et al., 2016). Areas where P − E correlates significantly with each ice core composite coincide with the geographical regions where the ice cores originate (Figure 1b). The four stacked ice core records for AP, western WAIS, central WAIS, and eastern WAIS are also significantly correlated with average P − E for the respective regions during 1979–2010 ($r \geq 0.5$, $p \ll 0.01$) from ERA-interim (Figure S1 in the supporting information). Both results suggest that the ice core composites represent well the regional snow accumulation.

The correlation between the ice core composite and averaged P − E from ERA-20C for the respective regions from 1900 to 2010 is significant at the 95% confidence interval (Figure 2), suggesting that ERA-20C has the skill to capture a part of snow accumulation variability in the composite time series since 1900. Both ERA-20C and ice core composites show negative trends over the western WAIS but positive trends over the AP, central WAIS, and eastern WAIS. Moreover, all the trends are also statistically significant for the AP, western WAIS, and eastern WAIS. In particular, ice core composites and ERA-20C have good agreement in both magnitude and statistical significance of the trends for the AP. The robust agreement may result from the key constraint of the assimilation of SLP observations centering on the AP for precipitation variability in ERA-20C because much of precipitation variability is driven by SLP changes. However, the two data sets show different trends over the central WAIS. No significant trend is seen in the ice core composite, whereas ERA-20C reveals a statistically significant increasing trend. Regardless of the differences in trend magnitudes, the directions of the changes in P − E in the ERA-20C are consistent with those derived from the ice core composites. Therefore, ERA-20C is considered to be able to represent the interannual variability in regional snow accumulation and the direction of the trends over the WAIS since 1900.

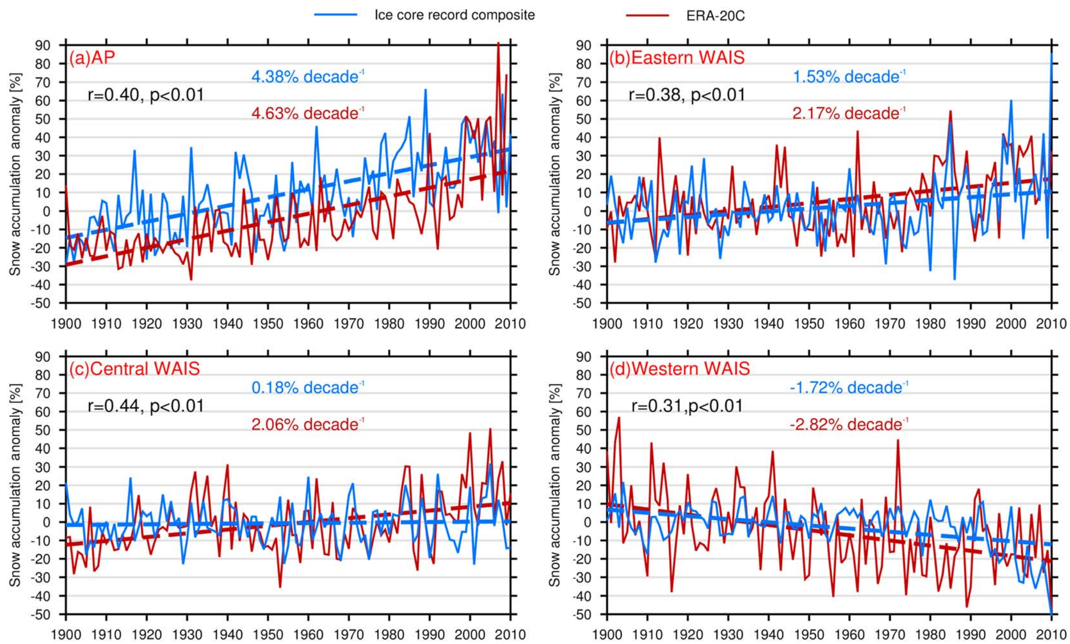

Figure 2. Temporal variability in snow accumulation from ice core composite and ERA-20C over the (a) AP, (b) eastern WAIS, (c) central WAIS, and (d) western AIS. Linear trend values and correlation coefficient between ice core composite and ERA-20C are also shown.

3.2. Changes in Ice Core Snow Accumulation Composites Since 1900

At 4.38% decade^{-1}, AP has experienced the most change in the observed accumulation rate between 1900 and 2010 among the four WAIS subregions (Figure 2). In particular, the increase in the AP snow accumulation over the twentieth century is greatly enhanced since the 1950s (8.92% decade^{-1} during 1950–2010), in accordance with a concurrent warming based on ice core stable isotopic composition records (Abram et al., 2013; Jones et al., 2016; Thomas et al., 2009). However, the lack of trends in the snow accumulation since the late 1990s does not correspond with the significant cooling over the same period (Turner et al., 2016). Although the trends are smaller in magnitude than those of the AP, eastern WAIS and western WAIS experience a significant increase and decrease in snow accumulation during 1900–2010, respectively. In contrast, the linear trend is weak and not significant for snow accumulation in the central WAIS (at only 0.18% decade^{-1}). In sum, contrasting trends exist for snow accumulation over the WAIS: AP and eastern WAIS are characterized by a significantly positive trend, whereas the trend for western WAIS is significantly negative from 1900 to 2010. No significant change in snow accumulation is found over the central WAIS for the same period.

3.3. Role of Sea Level Pressure in Ice Core Snow Accumulation Variability

The SLP data derived from ERA-20C and ERA-interim are highly correlated for 1979–2010 at each grid point (Figure S2). This suggests that the quality of the ERA-20C annual mean SLP is as good as that of the ERA-Interim for the overlapping period (1979–2010). Some skill of ERA-20C is assumed for the SLP variability prior to 1979 due to the assimilation of SLP observations. We compare the spatial correlations between each annual ice core snow accumulation composite and gridded SLP from ERA-interim (1979–2010) and ERA-20C (1900–2010) (Figures 3a and 3b). Although the extent of statistically significant correlations ($p < 0.05$) for ice core composites over the WAIS subregions (except the western WAIS) is smaller for 1900–2010 than for the period 1979–2010, the dominant spatial correlation patterns are very similar for the two timespans: with the significant SLP correlation over the Bellingshausen and Amundsen Seas for the AP ice core snow accumulation, the Amundsen Sea for eastern WAIS ice core composite, the Drake Passage for ice core composite over the central WAIS, and the Bellingshausen Sea for the western WAIS ice core composite. This exhibits a stable relationship between snow accumulation and SLP before and after 1979.

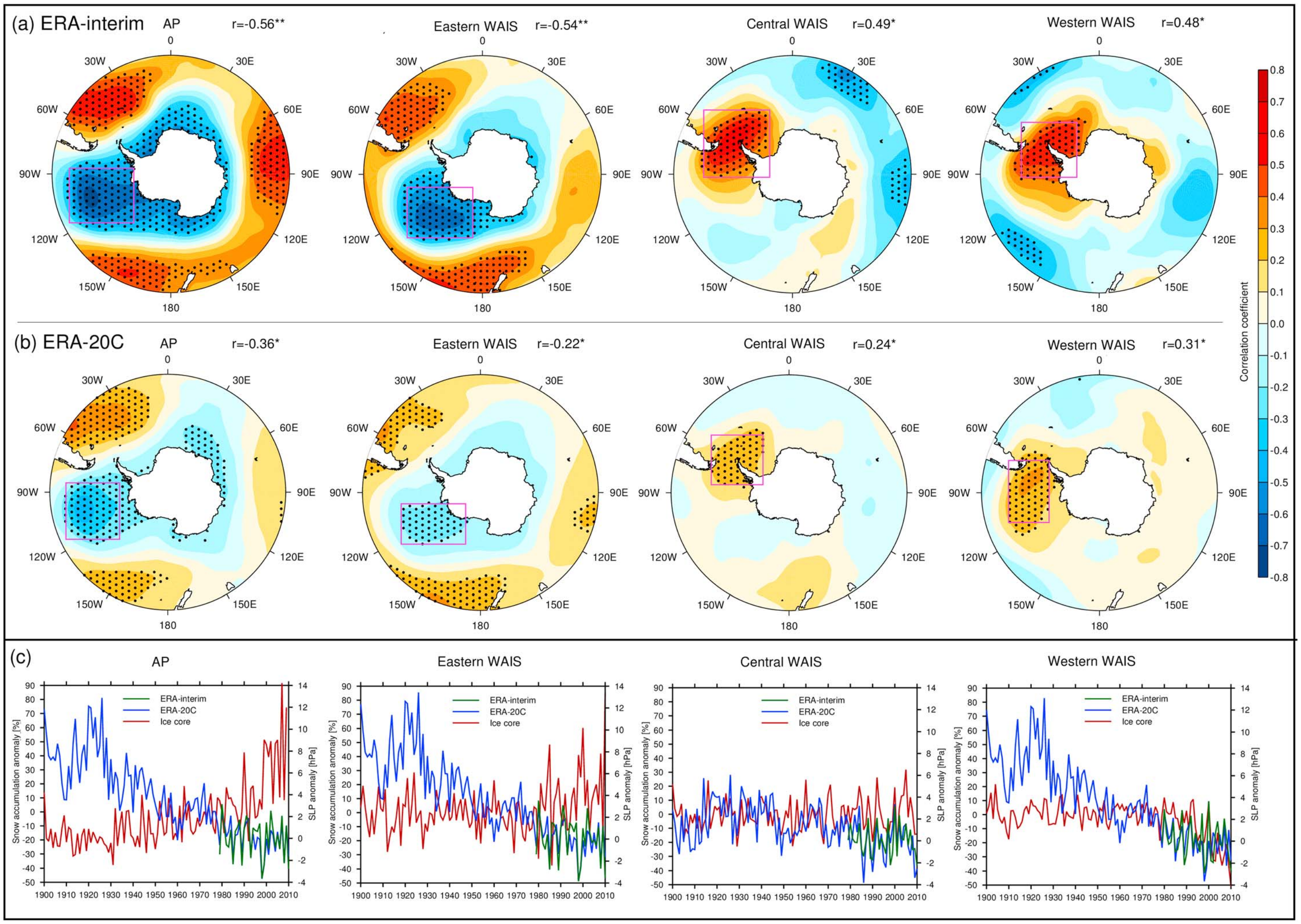

Figure 3. Spatial correlation of regional ice core snow accumulation composites with annually averaged SLP from (a) ERA-interim (1979–2010) and (b) ERA-20C (1900–2010). The dotted areas are at the 95% confidence level. (c) Time series of ice core snow accumulation composites and annual SLP averaged in each corresponding significant correlation field (Figures 3a and 3b, highlighted box) from ERA-interim and ERA-20C.

The AP snow accumulation variability since 1900 has a significant negative correlation with ERA-20C SLP across the Bellingshausen Sea and Amundsen Sea where, in contrast, the correlations for the western WAIS snow accumulation are significantly positive. Significant negative correlations ($p < 0.05$) between eastern WAIS accumulation and SLP in ERA-20C also exist in the Amundsen Sea sector. The areas with significant correlations are dominated by the Amundsen Sea low (ASL), a key component of the climatological circulation (Raphael et al., 2016), which plays an important role in precipitation variability over West Antarctica through controlling circumpolar westerlies and atmospheric moisture transport (e.g., Hosking et al., 2013; Tsukernik & Lynch, 2013; Thomas et al., 2008, 2015). Hosking et al. (2013) have reported that SLP in this region has been decreasing in recent decades. Thus, both the increase in snow accumulation over the AP and eastern WAIS and decrease over western WAIS between 1900 and 2010 are linked to the decline in SLP within the ASL sector. The duration of ASL deepening enhances the clockwise rotation of air masses and warm moisture advection along the eastern flank of the low-pressure system (Genthon et al., 2005; Thomas et al., 2015). This process increases moisture advection from the north to the AP and eastern WAIS, leading to increase in snow accumulation, and conversely decreases moisture availability to the western WAIS, and hence the decreased snow accumulation on this region. Moisture transport is dependent on not only the depth of the ASL but also its longitudinal position, which shifts to the Bellingshausen Sea in summer and westward to the Ross Sea in winter (Hosking et al., 2013). As the ASL moves farther east toward (the Bellingshausen

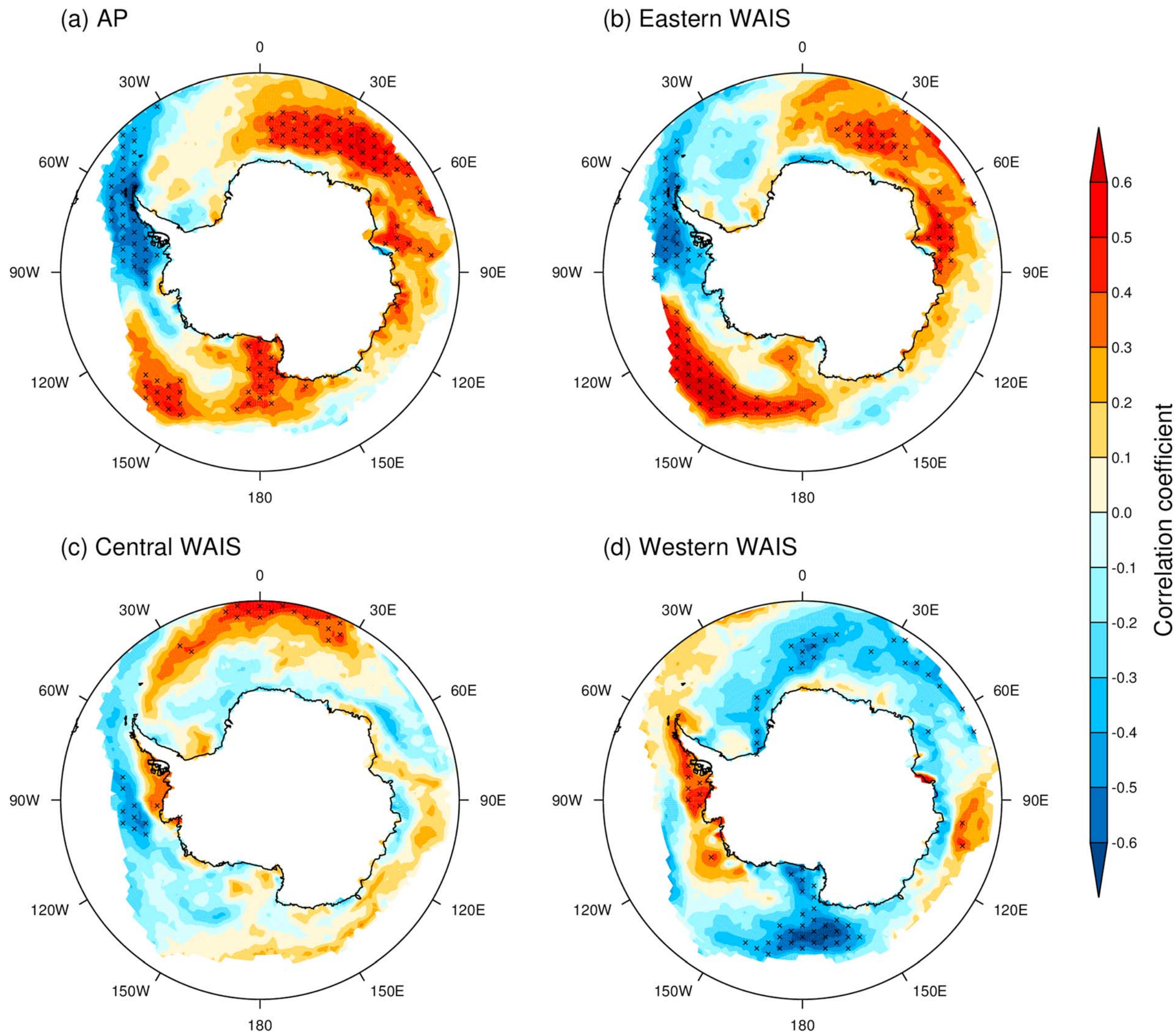

Figure 4. Spatial correlation of regional ice core snow accumulation composites with sea ice concentration (1979–2010). Crossed regions are at the 95% confidence level.

Sea), it will result in the strengthened northerly flow, which pushes warm moisture toward the AP, and thus increase precipitation. As the ASL is located farther west (the Ross Sea), it enhances the southerly flow over the western Ross Sea, which extends over the Antarctic land and precludes the warm moisture transport to the western WAIS, causing regional precipitation decrease. The central WAIS may get a mixture of the effects of the ASL on the precipitation over the western WAIS, AP, and eastern WAIS, due to the ASL location variability between summer and winter. These effects would be counteracting (increasing (decreasing) precipitation over the AP and eastern WAIS (the western WAIS)), and thus, the central WAIS experiences insignificant snow accumulation variability since 1900. Spatial correlation suggests that the Drake Passage SLP variability also plays an important role in snow accumulation in this region. If SLP over the Drake Passage increases, it can drive the enhanced northerly flow to the central Amundsen Sea, bringing more moist air to the central WAIS.

3.4. Relationship Between Sea Ice and Ice Core Snow Accumulation Variability

Sea ice is an important driver for snow accumulation variability over the WAIS due to its inhibition of heat and moisture exchange between the atmosphere and the ocean. Figure 4 shows the correlations between each annual ice core snow accumulation composite and sea ice concentration from 1979 to 2010. The ice core composites over the AP and eastern WAIS show significant negative correlations with sea ice concentration in the Bellingshausen Sea. Therefore, the upward trends in the AP and eastern WAIS snow accumulation throughout the twentieth century are expected as the decrease in the sea ice extent occurs over the same period. Abram et al. (2010) has reported a progressive decline in sea ice in the Bellingshausen Sea since 1900, with the current sea ice retreat suggested as the strongest during the past century (Porter et al., 2016). The declining sea ice enhances atmospheric water vapor content and increase poleward atmospheric moisture transport from the ocean to the AP and eastern WAIS (Tsukernik & Lynch, 2013). Strong negative correlations between ice core composite over the western WAIS and sea ice extent are also observed in a large part of the Ross Sea, with the correlation values of < -0.6, which means that $>36\%$ variance in the snow accumulation is explained by sea ice variability. Tuohy et al. (2015) have reported that a large fraction of precipitation over the western WAIS originates from the Ross Sea. Thus, the significant decrease in snow accumulation over the western WAIS is associated with increased sea ice extent over the Ross Sea sector throughout the twentieth century (Thomas & Abram, 2016), as sea ice increase is related to the enhanced meridional flow resulting from the ASL deepening, declining the availability of warm moisture to the western WAIS. The correlation between the AP and eastern WAIS snow accumulation and sea ice concentration during 1979–2010 is significantly positive in the sector of western Amundsen Sea and Ross Sea but negative in the Bellingshausen Sea (Figure 4c). Similarly, the western WAIS snow accumulation shows strong positive correlations with sea ice in the Bellingshausen Sea, as opposed to those in the Ross Sea. The dipole correlations can be explained by the well-known dipole pattern in sea ice variability: increasing in the Ross Seas and decreasing in the Bellingshausen Sea (Figure S3a) (Hosking et al., 2013). The central WAIS snow accumulation variability is only significantly correlated with sea ice in small areas in the western Amundsen Sea, where sea ice extent does not show significant trends in recent decades (Figure S3a).

ASL index defined by Hosking et al. (2013) is positively correlated with sea ice concentration in the Bellingshausen Sea but negatively correlated with sea ice concentration in the sector of western Amundsen Sea and Ross Sea, significant at the 95% confidence level (Figure S3b). This reflects that the contrasting trends of positive (negative) sea ice in the Ross (Bellingshausen) sea are related to the deepening of the ASL. ASL deepening intensifies the southerly winds over the Ross Sea and increases sea ice extent in this region, and leads to the strengthened northerly wind, advecting warm air moist air to the Bellingshausen Sea and contributing to the decrease in the sea ice extent. Therefore, in addition to the direct response of ice core snow accumulation composites to changes in the sea ice over the corresponding seas, there are indirect linkage between the two large-scale climate phenomena such that they show similar responses to changes in the ASL.

Although the HadISST.2.2.0.0 data provide the possibility to determine whether the correlation patterns between ice core composites and sea ice during 1979–2010 are robust for the period prior to 1979, large uncertainty exists for Antarctic sea ice concentration prior to 1973 because many observational gaps are filled by estimation (Titchner & Rayner, 2014). Therefore, it is not surprising that the spatial correlation patterns between the ice core composites and sea ice extent for the period 1979–2010 weaken or even diminish when the analysis extends back to 1900 (Figure S4).

4. Conclusions

In this study, we perform a comprehensive assessment of regional snow accumulation changes over the WAIS since 1900 based on 37 ice core records. Aggregating a large number of ice cores can reduce the small-scale noise due to drifting snow erosion/deposition, and thus enhance the reliability of regional climate trends derived from these data. Four drainage-based ice core composites were found to be representative for regional snow accumulation variability by comparison with ERA-interim $P - E$, the most reliable reanalysis for the high latitudes of the Southern Hemisphere (Bromwich et al., 2011; Wang et al., 2016). We also compare ERA-20C with these composite records to evaluate its skills in simulating snow accumulation. ERA-20C is able to capture interannual variability and the direction of trends in each drainage-scale ice core snow accumulation composite since 1900. It is very important to have a reliable reanalysis available to investigate snow accumulation and its relationship with atmospheric circulation before 1979.

Based on the regional ice core composites, we find a distinct dipole pattern of increasing snow accumulation over the AP and eastern WAIS and decreasing snow accumulation over the western WAIS in the last 100 years.

ERA-20C reproduces the dipole pattern of snow accumulation trends between 1900 and 2010. This dipole pattern is related to the deepening of the ASL, which enhances northerly winds driving more warm moist air along its eastward flank to the AP and eastern WAIS, and at the same time increases the occurrence of off-shore continental flow leading to the decrease in precipitation over the western WAIS. Another possible control for snow accumulation in the WAIS is sea ice variability. The observed decrease in sea ice in the Bellingshausen Sea can lead to higher surface temperatures, greater evaporation from the ocean surface, and more poleward atmospheric moisture transport onto the AP and eastern WAIS. At the same time, an increase in sea ice in the Ross Sea could go against the active moisture transport to the western WAIS. No significant trend in the central WAIS ice core snow accumulation composite from 1900 to 2010 could be linked with the mixture of the counteracting ASL effects on the precipitation over the western WAIS and the AP, and a lack of trend in the sea ice in the part of western Amundsen Sea.

Acknowledgments
This work was supported by the National Natural Science Foundation of China (41576182 and 41330526), Outstanding Youth Fund of Shandong Provincial Universities (ZR2016JL030), National Key Basic Research Program of China (2013CBA01804), and Scientific Research Foundation for the introduction of talent by Shandong Normal University. We are grateful to the two anonymous reviewers for their valuable comments and suggestions. ERA-interim and ERA-20C data are downloaded at https://www.ecmwf.int/. ERSST.v4 data are derived from Earth System Research Laboratory (https://www.esrl.noaa.gov/psd/data/gridded/data.noaa.ersst.v4.html). Ice core data are available at http://www.pagesigbp.org/ini/wg/antarctica2k/data. We download HadISST.2.2.0.0 data on http://www.metoffice.gov.uk/hadobs/hadisst2/.

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