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Key Points:
- Extreme precipitation events explain 70% of the interannual variance of Antarctic snowfall
- Extreme precipitation events are particularly important over western West Antarctica and on the Ross and Amery Ice Shelves
- Tropical climate variability is important in modulating the frequency of extreme precipitation events in the West Antarctic sector

Supporting Information:
- Supporting Information S1

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The Dominant Role of Extreme Precipitation Events in Antarctic Snowfall Variability

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Abstract Antarctic snowfall consists of frequent clear-sky precipitation and heavier falls from intrusions of maritime airmasses associated with amplified planetary waves. We investigate the importance of different precipitation events using the output of the RACMO2 model. Extreme precipitation events consisting of the largest 10% of daily totals are shown to contribute more than 40% of the total annual precipitation across much of the continent, with some areas receiving in excess of 60% of the total from these events. The greatest contribution of extreme precipitation events to the annual total is in the coastal areas and especially on the ice shelves, with the Amery Ice Shelf receiving 50% of its annual precipitation in less than the 10 days of heaviest precipitation. For the continent as a whole, 70% of the variance of the annual precipitation is explained by variability in precipitation from extreme precipitation events, with this figure rising to over 90% in some areas.

Plain Language Summary The Antarctic ice sheet is extremely important because of its possible contribution to sea level rise and through the climate records than can be reconstructed using chemical signals locked in the ice. The mass of the ice sheet is constantly changing because of the ice gained by snowfall and the loss of ice at the margins via iceberg calving and melt through contact with relatively warm water masses. The amount of snow falling on the Antarctic is highly variable and dependent on the meteorological conditions over the Southern Ocean and the penetration of marine air into the interior. We show that extreme snowfall events, defined at the heaviest 10% of daily precipitation amounts, contribute a high percentage of the annual snowfall and are the main factor controlling the year-to-year variability of snowfall across the continent. This has implications for the reconstruction of past climate records using data from ice cores and the selection of future ice core drilling sites.

1. Introduction

Snowfall is the primary input to the Antarctic ice sheet and its variability and change have an impact on the ice sheet mass balance and therefore the contribution of the continent to sea level rise (Shepherd & Wingham, 2007; Wingham et al., 2006). A knowledge of the origins of the precipitating airmasses and the temporal distribution and magnitude of the precipitation events are also essential for the correct interpretation of climate proxies from ice cores, such as snow accumulation, stable water isotopes (a proxy for past surface temperatures and moisture sources), and chemical records (vital for accurate dating of ice cores and reconstructing large-scale modes of atmospheric variability (Thomas et al., 2017).

Across Antarctica, ice accumulates from light snowfall episodes, which frequently fall as near-continuous clear-sky precipitation (Bromwich, 1988; Stenni et al., 2016; Walden et al., 2003). However, there are also relatively short-lived intrusions of maritime air giving heavier precipitation, which are often in the form of extreme precipitation events (EPEs) occurring during periods of strong meridional flow (Noone et al., 1999) when the midtropospheric planetary waves are amplified (Hirasawa et al., 2000; Massom et al., 2004). Some EPEs at coastal locations are associated with narrow ribbons of moist air arriving from midlatitudes known as “atmospheric rivers” (Zhu & Newell, 1998), and these events can also be important in giving relatively large amounts of precipitation at interior locations (Genthon et al., 1998; Gorodetskaya et al., 2014). EPEs are often linked to one polarity of the principal modes of atmospheric circulation

Table 1
Precipitation, Location, and Orographic Height Information for the 10 Sites Discussed in Detail

	Latitude	Longitude	Elevation (m)	Mean Annual Model Precipitation (mm)	Highest Daily Precipitation (mm)	90th Percentile (mm)	R^2
Dronning Maud Land	75.00°S	0.33°W	2875	67.2	6.1	0.87	0.91
High plateau	79.85°S	90.02°E	3793	23.8	1.11	0.25	0.78
Law Dome	66.73°S	112.75°E	1325	470.2	32.05	4.23	0.82
Dome C	75.35°S	123.33°E	3242	28.8	2.77	0.39	0.85
Ross Ice Shelf	79.85°S	179.83°E	51	109.1	15.72	1.16	0.95
Ocean	70.26°S	149.99°W	0	588.9	22.25	4.31	0.64
WAIS Divide	79.68°S	112.33°W	1779	165.6	9.36	1.26	0.86
Gomez	74.06°S	70.86°W	1201	805.2	60.76	7.48	0.81
West Peninsula	70.01°S	66.73°W	1477	984.6	87.88	9.31	0.89
East Peninsula	69.88°S	60.02°W	0	444.6	38.8	4.14	0.82

Note. The elevations refer to the orographic heights in the RACMO2 model. The R^2 values are the fraction of the variance of the annual mean precipitation explained by EPEs. A number of the locations selected are close to ice core drilling site, with model data provided here and elsewhere to aid in the interpretation of the ice core records. We have not extrapolated the model data to the exact locations of the ice core drilling sites as many of the EPEs were associated with small-scale features, such as atmospheric rivers, and we did not want to smooth the data and lose the details of the spatial pattern of EPEs. It should therefore be noted that the annual model precipitation values will not agree exactly with accumulation values determined from the ice core records because of differences in the locations of the model grid points and drilling sites, differences in the time periods considered, and the fact that blowing snow episodes will affect the ice core records.

variability at southern high latitudes (Marshall et al., 2017), such as the Southern Annular Mode (SAM) or the Pacific-South American patterns, the latter associated with El Niño–Southern Oscillation variability.

EPEs have been studied at several locations across the Antarctic (Birnbaum et al., 2006; Braaten, 2000; Fujita et al., 2011; Gorodetskaya et al., 2014; Schlosser et al., 2010; Yu et al., 2018), although the investigations have been limited by the sparseness of in situ observations and the relatively coarse horizontal resolution of atmospheric reanalysis fields. We therefore have no knowledge regarding the nature and importance of EPEs across the Antarctic as a whole, which is a significant problem in the interpretation of climate signals in ice cores and in the determination of the future mass balance of the Antarctic ice sheet.

Over recent years, the performance of limited-area, high-resolution regional climate models has advanced rapidly to the point where they can now accurately simulate the temporal and spatial detail of Antarctic precipitation with unprecedented accuracy (Lenaerts et al., 2013; Marshall et al., 2017), allowing their use in studies of Antarctic EPEs. Here we therefore use the output of a run of the RACMO2 limited area, high horizontal resolution atmosphere-only model to investigate the nature, importance, and temporal variability of EPEs across the whole Antarctic continent. The performance of this model has been verified extensively and is known to have a good representation of the Antarctic precipitation field (Figure S1), which can resolve precipitation on the scale of small drainage basins.

In this study, we quantify for the first time the impact of EPEs across the Antarctic continent and explain their role in modulating the total Antarctic precipitation. As in a number of previous studies, we take an EPE to be a daily precipitation total that is within the top 10% of the long-term record of daily precipitation amounts at a location (see section 2). We focus particularly on 10 sites (see Table 1 and Figure 1) that represent different Antarctic precipitation regimes from the open ocean and coastal high precipitation zone to the desert conditions of the high plateau. A number of these locations are close to important ice core-drilling sites that have revealed dramatic changes in snow accumulation during the twentieth century (e.g., Gomez, at the base of the Antarctic Peninsula (Thomas et al., 2008)) and reconstructions spanning the past 2,000 (Law Dome (Roberts et al., 2015)) to 31,000 years (West Antarctic Ice Sheet (WAIS) Divide (Fudge et al., 2016)).

We have elected to examine precipitation as it is the largest component of the surface mass balance (SMB) and is well represented by the RACMO model. The other terms of the SMB include evaporation from the snow surface and the impact of blowing snow. Evaporation decreases very rapidly away from the coast and is essentially zero during the winter season (Grieger, 2016). On the other hand, blowing snow can locally add or remove large amounts of snow at some locations, especially in steep glacial valleys. We examined the RACMO daily SMB data and found that across most of the continent the long-term SMB and precipitation

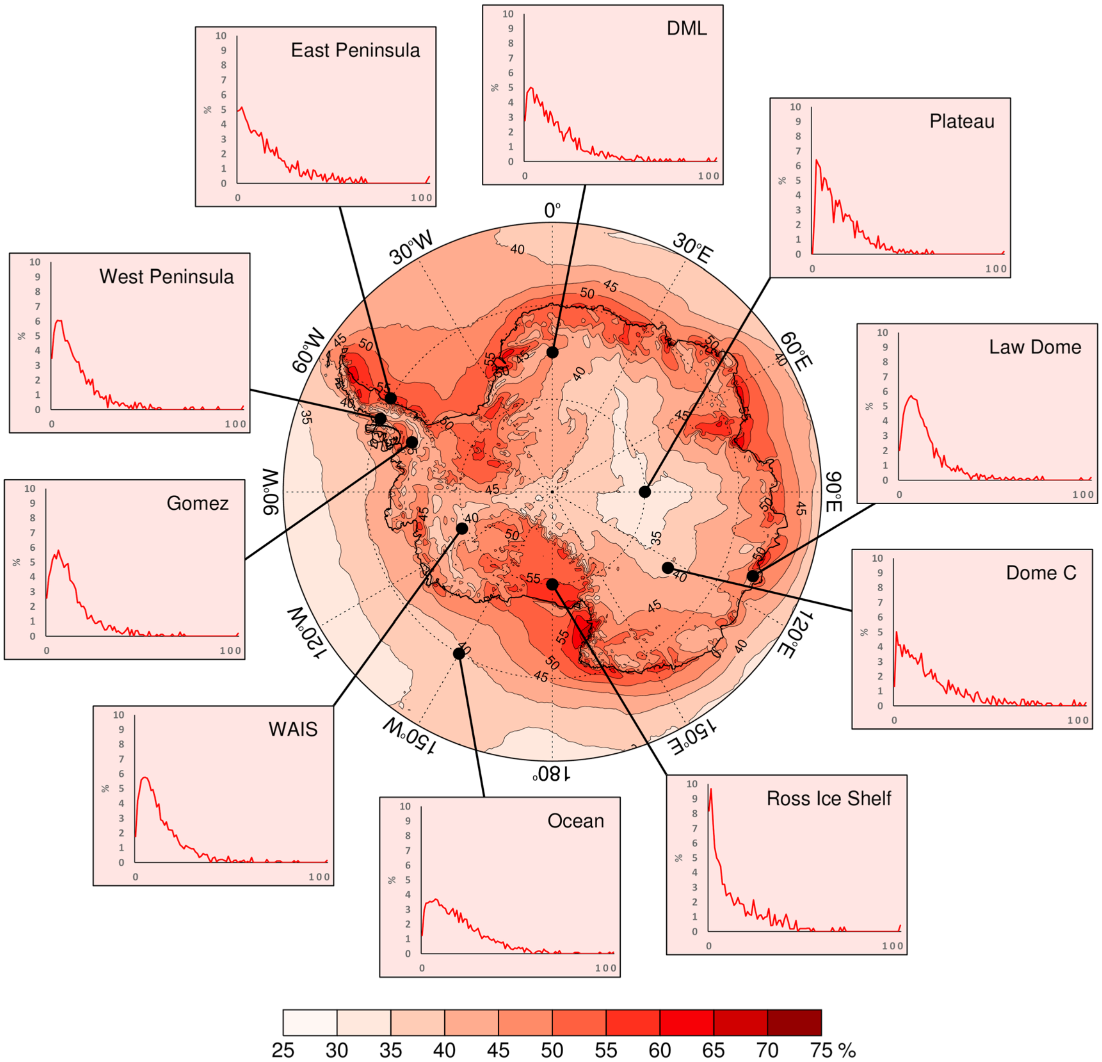

Figure 1. The contribution of EPEs to the annual precipitation. The contours and colors indicate the percentage of the annual precipitation that comes from EPEs. The boxes show the percentage of precipitation (vertical axis) in each of 100 equally spaced bins covering the range of daily precipitation values at each location, which is indicated as 0 to 100% on the horizontal axis. The locations of the 10 sites are given in Table 1.

agreed to within 10%, although many individual large SMB events were associated with blowing snow rather than precipitation. Our focus is therefore on EPEs, which are closely tied to synoptic events and decadal atmospheric variability.

2. Methods

2.1. Model

We analyzed EPEs across high southern latitudes for the period 1979–2016 using the output of the atmosphere-only, limited area model RACMO2, version 3p2 (van Wessem et al., 2014), which has a horizontal resolution of approximately 27 km. A number of operational numerical weather prediction models have a higher horizontal resolution, but these models have changed several times over recent decades and their representation of EPEs will have changed. We therefore elected to use RACMO2 data because of its long-term consistency and because its performance has been extensively evaluated. It has been shown to have a good simulation of precipitation across the continent (Figure S1) with a bias that is less than 5% of the in situ observations of accumulation (van Wessem et al., 2014).

2.2. Determination of Extreme Precipitation Events

The study was based on daily total precipitation data with a precipitation day being taken as one with more than 0.02 mm. This is well below the threshold of a precipitation day used in the extrapolar regions, but such a low value is necessary when considering precipitation on the high Antarctic plateau. The graphics in this paper were recomputed with a range of threshold values, but these made no significant difference to the conclusions, as we are concerned primarily with EPEs. An EPE was taken to be a period of one or more consecutive days when daily precipitation was greater than the 90th percentile of the whole time series of daily precipitation values.

A number of different statistical distributions were fitted to the distributions of daily precipitation values at single locations (such as shown on Figure S2) to investigate whether this would enable the spatial distribution of EPE frequency to be illustrated using the distribution parameters. The most successful was the generalized extreme value distribution (Coles, 2001). However, because of the large variability in the shape of the distributions across the continent, the quality and robustness of the generalized extreme value fit to the precipitation data varied considerably so we have based our analysis solely on the actual precipitation from the model.

While there is no single agreed definition of an EPE, we have followed earlier studies (e.g., IPCC, 2012; Kanada et al., 2010; Moberg et al., 2006; Orlowsky & Seneviratne, 2011; Pryor et al., 2009; Vavrus et al., 2015) and taken such an event to be one or more days when the daily precipitation exceeds a percentile value of the 1979–2016 distribution, here using the 90th percentile.

2.3. Atmospheric Circulation

The atmospheric circulation variability was investigated using the fields from the European Centre for Medium-range Weather Forecasting Interim reanalysis (ERA-Interim; Dee et al., 2011). These fields have a grid spacing of $0.7 \times 0.7°$ and are considered the best reanalysis data set for depicting the atmospheric circulation of high southern latitudes (Bracegirdle & Marshall, 2012). The ERA mean sea level pressure and geopotential height data were used rather than the comparable RACMO2 fields since the ERA data gave greater spatial coverage, and in the coastal region the data are very comparable since the lateral boundary conditions for RACMO2 are taken from ERA-Interim. We recomputed the results of our study using the ERA-Interim precipitation data, and although the detailed spatial structure of the EPEs was not as good, the same overall conclusions were obtained.

Correlations and significance levels were computed from gridded data sets using the nonparametric Kendall's tau, a statistic based on the number of pairings of rankings that occur in consistent and inconsistent orders.

We used the Southern Annular Mode index of Marshall (2003) and the Oceanic Niño Index (ONI) data were obtained from the website of the U.S. National Weather Service Climate Prediction Center (http://origin.cpc.ncep.noaa.gov/products/analysis_monitoring/ensostuff/ONI_v5.php).

3. Results

In the coastal region, EPEs are associated with low mean sea level pressure in the circumpolar trough to the west of each site (Figure S3). At interior locations, such as Dome C and WAIS Divide, EPEs occur when the midtropospheric flow is strongly meridional, with a trough to the west of the location (Figure S3). The majority of EPEs at the 10 sites considered here lasted for just one day (Table S1) but on average 22% and 6% of the events lasted two and three days, respectively. EPEs have a short duration over ocean locations where there are many mobile weather systems, but last longer where the circulation becomes blocked (Bromwich, 1988; Massom et al., 2004; Scarchilli et al., 2011), such as on the western side of the Antarctic Peninsula and at locations south of the main storm track, such as on the Ross Ice Shelf. Of the sites considered, the longest-duration EPE occurred at Gomez near the base of the Antarctic Peninsula. This was a nine-day event over 7–15 May 2001 when the model had 154 mm of precipitation at the site or 18% of the total for the year. As with many of the longer-duration events, the precipitation was associated with a quasi-stationary high-low surface pressure couplet that fed moisture onto the continent (Figure S4).

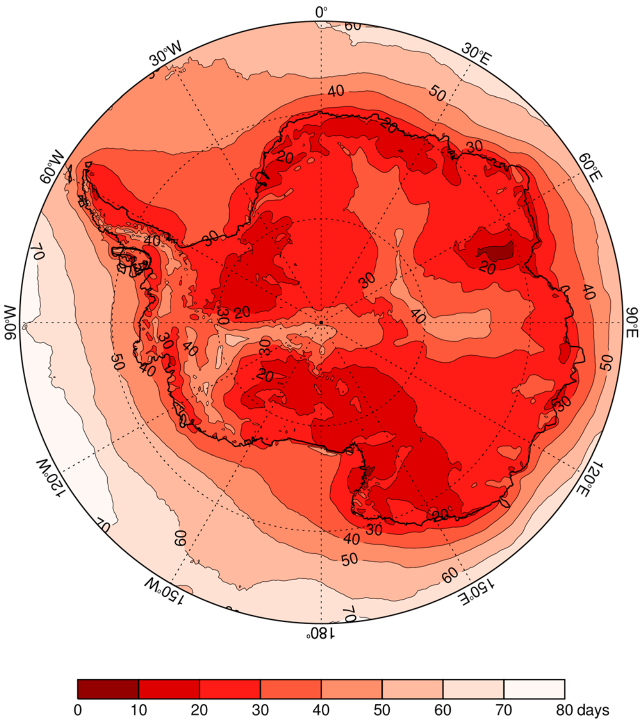

Figure 2. The importance of the highest precipitation events during the year. The number of days of the highest, ranked precipitation that gives 50% of the annual total. Darker colors indicate where the EPEs are more important.

The importance of EPEs in influencing the total annual precipitation varies across the continent because of differences in the form of the daily precipitation frequency distributions at the 10 sites (Figure S2). At a typical ocean location (70°S, 150°W), there are frequent medium daily precipitation amounts leading to a broad distribution compared to many continental sites. EPE variability is therefore less important in determining total precipitation variability. An exception at more northerly latitudes is the eastern side of the Antarctic Peninsula, which is south of the main storm track and relatively dry, and which receives fewer medium daily precipitation amounts.

At coastal locations, such as Law Dome on the edge of East Antarctica, there is a peak at the lower end of the distribution, but there are fewer medium daily precipitation amounts than over the ocean areas and, as in many parts of the coastal areas, the larger daily precipitation amounts are more important in dictating the annual total. In areas well south of the major depression tracks, such as on the Ross Ice Shelf, there is a very rapid drop in the frequency of large daily precipitation amounts, giving a very narrow peak to the distribution; thus, these larger daily precipitation amounts provide a relatively large contribution to the annual total precipitation.

The importance of large daily precipitation events can be quantified across the whole continent via the percentage of the annual precipitation that comes from EPEs (Figure 1). EPEs contribute more than 40% of the total annual precipitation across much of the continent, with some areas receiving in excess of 60% of the total from these events. Orography is extremely important in controlling the southward penetration of maritime airmasses and therefore the occurrence of EPEs. The greatest contribution of EPEs to the annual total is in the coastal areas of the continent and especially on the ice shelves. On the Amery Ice Shelf 50% of the annual precipitation is received in less than 10 days of the heaviest precipitation (Figure 2). This situation arises because of the unique orography of the region, which normally shelters the location from maritime airmasses, but where quasi-stationary depressions in the circumpolar trough can occasionally introduce moist maritime airmasses, which have a very large impact in these relatively dry regions. At one location on the edge of the Amery Ice Shelf (71.40°S, 68.73°E), an EPE on 11 September 1994 gave 44% of the year's precipitation—the most extreme daily precipitation event in terms of the percentage contribution seen at any location in the RACMO2 data.

The differing roles of EPEs on a regional scale can be appreciated via the situation across the Antarctic Peninsula. The western side has a maritime climate with many depression to the west that give small to moderate amounts of precipitation on a high percentage of days, resulting in a relatively small role for EPEs. In contrast, the eastern side has a relatively dry climatological southerly flow, although occasionally strong westerlies can bring airmasses to the region that have little moisture because of the Foehn effect. Incursions of moist air from the north result in significant accumulation, so that EPEs are much more important than on the western side of the peninsula (Figure 2).

One region where EPEs have a particularly important role in controlling the total precipitation is Victoria Land and especially the region on the western side of the Ross Sea and inland of the Terra Nova Bay region. This is a dry area that has experienced a significant decrease in snow accumulation since the 1950s (Thomas et al., 2017). Strong katabatic winds flow down to the coast (Bromwich, 1989) impeding the penetration of many maritime airmasses into the interior, thus increasing the influence of the heavy snowfall events that do occasionally arrive.

Over the very highest parts of the Antarctic plateau in the Dome A, Ridge B, and toward Dome F areas, intrusions of maritime air are much rarer than in the coastal region, so the annual precipitation amount is dictated more by frequent clear-sky precipitation (Sato et al., 1981) episodes (Figure 1). The role of EPEs is therefore less important at the highest elevations, with more than 40 of the highest precipitation days required to give 50% of the annual total (Figure 2).

The importance of orography in influencing the nature of the precipitation is apparent in the central part of West Antarctica along 90°W. This area has higher orography compared to the regions to the east and west, but is a region of frequent intrusions of air from the Southern Ocean, which are forced up to higher elevations, giving greater cloud and precipitation (Nicolas & Bromwich, 2011) and reducing the importance of EPEs, with more than 50 days of the heaviest precipitation required to give 50% of the annual total (Figure 2). Cyclones, whether local or remote in relation to a location, are important in giving EPEs in all part of the Antarctic except the highest parts of the central plateau. The variability in the number of EPEs throughout the year at many locations is therefore strongly influenced by the semiannual oscillation, which is the cycle that controls the southward (northward) movement and deepening (weakening) of depressions in spring and fall (summer and winter; van den Broeke, 2000). The influence of the semiannual oscillation is most pronounced at more northerly latitudes, such as at the Gomez and DML ice core sites, where there are greater numbers of EPEs in the fall and spring (Figure S5), but a signal of the semiannual oscillation can still be detected at locations well into the interior.

This seasonal variability in the occurrence of EPEs can be important when interpreting climate proxies in ice cores, such as stable water isotopes. However, the seasonal fields showing the importance of EPE in dictating the total precipitation (Figure S6) are all very similar to the annual data, although in summer, when there is less cyclonic activity, EPEs have a slightly smaller influence over the ocean and in the coastal areas.

EPEs play an important part in controlling the interannual variability of precipitation. For the continent as a whole, 70% of the variance of the annual precipitation is explained by variability in precipitation from EPEs, with this figure rising to over 90% in some areas (Figure 3). EPEs are particularly important in this regard in an arc from the western Ross Sea, across the Ross Ice Shelf and western Marie Byrd Land toward the Ronne Ice Shelf. At one location in West Antarctica (83°S, 146°W), 97% of the variance in the annual precipitation over 1979–2016 was accounted for by variability in the precipitation from EPEs.

Seasonally, the magnitudes of the amount of interannual variability that are explained by EPEs (Figure S7) are broadly similar to the annual data (Figure 3). In all seasons the percentage of variance explained by EPEs is large on the ice shelves and low over the ocean and the high parts of the plateau. The year-to-year variability in the seasonal contributions of the EPEs to the total precipitation at the various sites (Figure S7) is larger than for the annual data, and is particularly pronounced on the Ross Ice Shelf where in some years EPEs make no contribution at all, yet in other years dominate the signal depending on the synoptic situation. West Antarctica has the strongest teleconnections to tropical Pacific climate variability (Marshall et al., 2017; Turner, 2004), particularly affecting the interannual variability in many atmospheric and cryospheric parameters via changes in the Amundsen Sea Low (ASL; Raphael et al., 2015). During El Niño (La Niña) events the ASL is weaker (stronger) and there is more (less) northerly flow toward the Ross Ice Shelf and more (fewer) intrusions of maritime air to this region. Therefore, when El Niño–Southern Oscillation is in its El Niño phase the stronger northerly flow into the Ross Sea region gives a greater number of EPEs. This results in the annual total of precipitation from EPEs per year on the eastern Ross Ice Shelf and western Marie Byrd Land being significantly correlated at $p < 0.05$ with the ONI (Figure S8). The relationship between the amount of precipitation from EPEs and the ONI is less strong and not significant on the western side of the Ross Ice Shelf and over the western Ross Sea because these areas are affected by strong off-continent katabatic winds that impede the intrusions of maritime air and their signal of tropical variability. The relationship between the amount of precipitation from EPEs and the ONI varies between seasons (Figure S9). The teleconnection between the ASL and the tropical Pacific is strongest during the winter and spring (Clem & Fogt, 2013; Turner, 2004), and in these seasons there is a couplet of positive (negative) EPE precipitation/ONI correlations over the Ross Sea (Bellingshausen Sea and eastern West Antarctica). However, the katabatic winds are strongest during the winter and limit the impact of tropical variability reaching the Ross Ice Shelf during this season.

The SAM is the primary mode of climate variability at high southern latitudes and the atmospheric circulation changes associated with variability in its phase include a deeper (weaker) ASL when the SAM index is positive (negative; Hosking et al., 2013). A deeper (weaker) ASL therefore gives stronger (weaker) northwesterly flow toward the western side of the Antarctic Peninsula and more (fewer) EPEs in this area

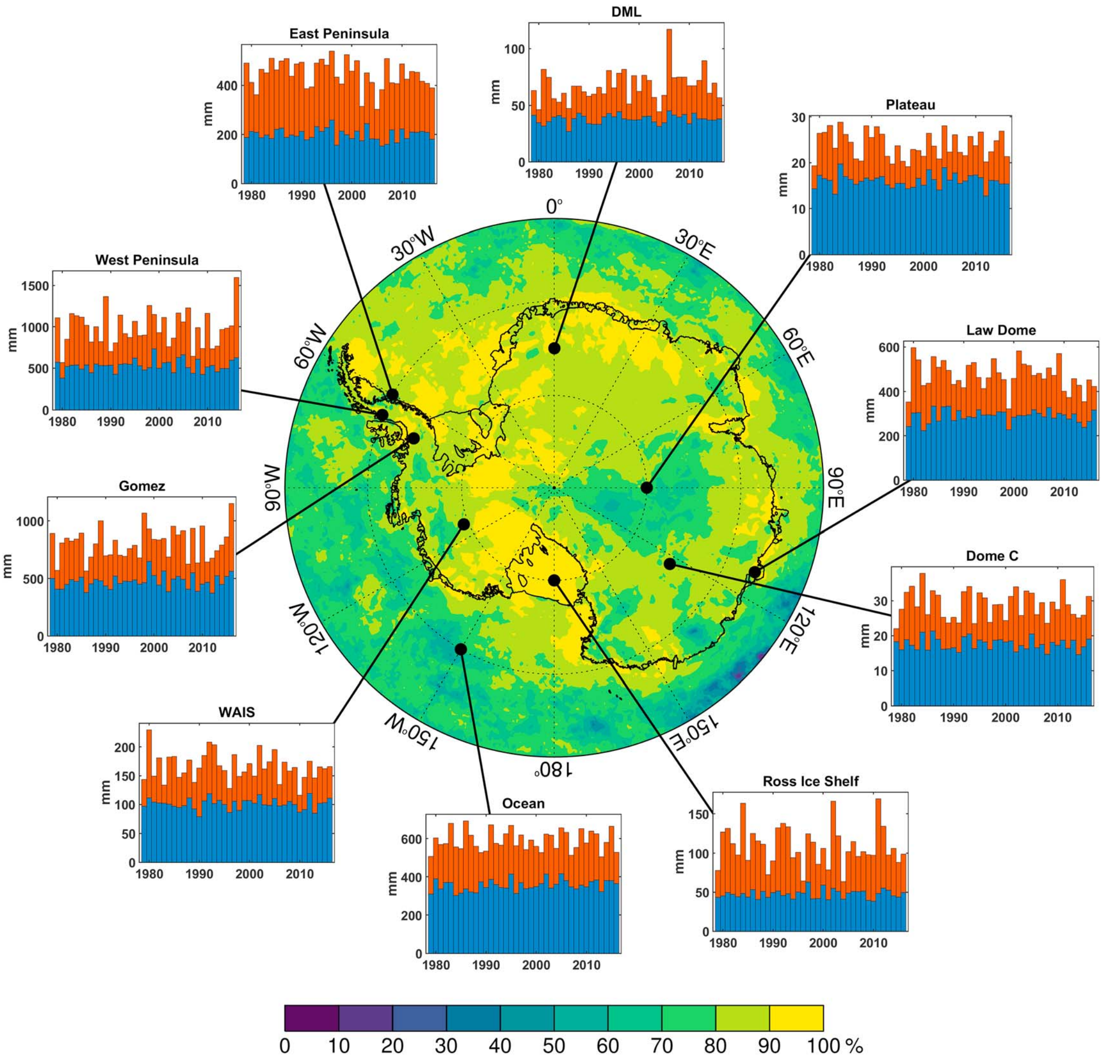

Figure 3. The role of EPEs in explaining the interannual variability of precipitation. The color shading indicates the percentage of the variance of the annual mean precipitation explained by EPEs. The boxes show the annual total precipitation from EPEs (red) and the residual (blue) for 1979–2016.

(Figure S8b). Similarly, a deeper (weaker) ASL gives stronger (weaker) flow off the Ross Ice Shelf and fewer (more) EPEs on the ice shelf. This pattern of correlation and anticorrelation is found in spring, fall, and winter, but is not apparent in summer when there is a minimum in cyclonic activity around the Antarctic (Figure S10). The largest and most coherent seasonal correlation pattern across the continent is in fall when the precipitation from EPEs over much of East Antarctica is anticorrelated with the SAM. Even though El Niño–Southern Oscillation/SAM effects are partly coupled (Fogt et al., 2011), overall, the eastern Ross Ice Shelf and western Marie Byrd Land receives most (least) EPEs when the SAM is negative (positive) and the tropical Pacific is in the El Niño (La Niña) phase.

Other parts of the continent also have more than 90% of the interannual variability of the total annual precipitation explained by variability in the number of EPEs (Figure 3), but this results primarily from local variability in the occurrence of depressions, especially those developing within the circumpolar trough, rather than the major modes of climate variability. There are a number of areas across the continent where less of the precipitation variability is explained by EPEs. These include a small area inland of the coast of East Antarctica near 68°S, 135°E and an inland region of West Antarctica from the Antarctic Peninsula to 120°W. These are both areas where the climatological easterly flow is forced up an orographic slope, increasing the smaller amounts of precipitation and decreasing the relative contribution from EPEs. There is a large area on the plateau along 100°E from the South Pole to 75°S where EPEs account for a smaller fraction of the interannual precipitation variability compared to the rest of the continent (Figure 3). This is an area of very high elevation where most of the precipitation comes from the smaller daily amounts (Figure 2) and maritime intrusions are particularly rare, so that the interannual variability of the precipitation is most strongly influenced by the non-EPE precipitation.

The trends in the annual total of precipitation from EPEs over 1979–2016 are small across most of the continent with only two large areas of statistically significant ($p < 0.05$) change in southern Dronning Maud Land and inland of the coast across 100–120°E (Figure S11). These are both areas where there have been significant trends in the annual precipitation total, as a result of greater ridging and amplification of planetary waves over East Antarctica resulting in more on onshore (offshore) flow close to 50°E (100°E). One area where there have been large temperature and circulation changes over 1979–2016 is the Antarctic Peninsula (Turner et al., 2005). This region experienced some of the largest temperature increases observed in the Southern Hemisphere during the second half of the twentieth century, but since the late 1990s there has been a regional cooling (Turner et al., 2016). This was reflected in an increase in the number of EPEs on the western side of the Antarctic Peninsula up until the end of the twentieth century followed by a subsequent decrease. During the twentieth century, positive trends in snow accumulation on the Antarctic Peninsula and eastern WAIS have contrasted with negative trends in snow accumulation in the western WAIS and Victoria Land (Thomas et al., 2017; Wang et al., 2017), consistent with a deepening ASL. However, there has been no significant change in the precipitation from EPEs over the period considered here (Figure S11).

4. Discussion and Conclusions

EPEs contribute a large proportion of the annual snowfall across the Antarctic and are the primary factor in controlling the interannual variability in accumulation. This has implications for the interpretation of chemical signals in ice cores, which are used extensively to reconstruct past surface temperatures, greatly increasing our understanding of Antarctic climate variability, especially in the preinstrumental period before the late 1950s. However, this is based on the observed relationship between isotopic composition of precipitation and surface air temperature. But ice core stable water isotope records are precipitation biased (mainly recording surface air temperature during snowfall events), and are thus highly susceptible to the occurrence of EPEs, which, in some years, can potentially weight the record to a single season or a small number of events. The importance of EPEs has not previously been appreciated, which will require a reconsideration of the biases in the records and the links between the ice core signals and the broad-scale high-latitude atmospheric circulation and tropical climate variability. It will also have implications for the selection of future ice core drilling sites and the reconstruction of long-term records of the modes of climate variability.

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