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J M A Macha, A N Mackintosh, F S McCormack, B J Henley, H V McGregor, et al.. Distinct Central and Eastern Pacific El Niño Influence on Antarctic Surface Mass Balance. *Geophysical Research Letters*, 2024, 51 (11), 10.1029/2024gl109423 . hal-04670442

HAL Id: hal-04670442

<https://hal.science/hal-04670442v1>

Submitted on 12 Aug 2024

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Geophysical Research Letters[®]



RESEARCH LETTER

10.1029/2024GL109423

Distinct Central and Eastern Pacific El Niño Influence on Antarctic Surface Mass Balance

Key Points:

- Central and Eastern Pacific El Niño events have distinctly different seasonal impacts on Antarctic surface climate
- Central Pacific El Niño accumulation anomalies develop earlier than Eastern Pacific El Niño, and persist through austral winter and spring
- Central Pacific El Niño impacts on West Antarctic accumulation are significantly greater than those of Eastern Pacific El Niño events

Supporting Information:

Supporting Information may be found in the online version of this article.

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Citation:







Macha, J. M. A., Mackintosh, A. N., McCormack, F. S., Henley, B. J., McGregor, H. V., van Dalum, C. T., & Purich, A. (2024). Distinct Central and Eastern Pacific El Niño influence on Antarctic surface mass balance. *Geophysical Research Letters*, 51, e2024GL109423. <https://doi.org/10.1029/2024GL109423>

Received 21 MAR 2024

Accepted 16 MAY 2024

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Abstract The El Niño-Southern Oscillation causes anomalous atmospheric circulation, temperature and precipitation across southern polar latitudes, but the influence of Central and Eastern Pacific El Niño events on Antarctic surface mass balance and snow accumulation has not yet been assessed. Here, we use reanalysis and reanalysis-forced regional climate model output and find that Central Pacific El Niño results in significantly increased snow accumulation in the western Ross Sea sector and significantly decreased snow accumulation in the Amundsen Sea sector. Eastern Pacific El Niño is associated with similar but weaker patterns, with some regional exceptions. In some areas, like Dronning Maud Land, or the Wilkes Subglacial Basin, the effect of El Niño on snow accumulation changes from increased to reduced accumulation depending on the type of El Niño. Our results show that projecting El Niño types is important for constraining future changes in Antarctic surface mass balance.

Plain Language Summary The El Niño-Southern Oscillation influences the climate in Antarctica with impacts on temperature, rainfall and snow accumulation. However, the effect of two different types of El Niño events, Central Pacific and Eastern Pacific El Niño, on the patterns of snow accumulation in Antarctica has not yet been studied. We show from reanalysis and reanalysis-forced regional climate model output that Central and Eastern Pacific El Niño events have distinct effects on Antarctic snow accumulation patterns. During Central Pacific El Niño events, there is an increase in snow accumulation in the western Ross Sea sector, and decrease in the Amundsen Sea region. Eastern Pacific El Niño events cause similar regional effects, but to a lesser extent. In some areas, like Dronning Maud Land or the Wilkes Subglacial Basin, the effect of El Niño on snow accumulation changes from increased to reduced accumulation depending on the type of El Niño. Our findings emphasize the importance of understanding projected changes in El Niño types, as these will impact the future of Antarctica's snow accumulation.

1. Introduction

The Antarctic Ice Sheet (AIS) has been losing mass for several decades due to regional ocean-driven increases in basal melting of ice shelves, iceberg calving and associated dynamic changes in ice discharge (Frieler et al., 2015; Fox-Kemper et al., 2021; Hanna et al., 2020, 2024; J.-Y. Lee et al., 2021). This ocean-driven mass loss is counteracted by mass gain in some regions of Antarctica, driven by processes underlying surface mass balance (SMB), that is, the sum of accumulation and ablation (melting) processes at the ice sheet surface (Agosta et al., 2013; Mottram et al., 2021). Snow accumulation, the major control on SMB in Antarctica, has been increasing over this period, although with significant spatial and temporal variability (Hanna et al., 2020; Noël et al., 2023). Understanding and projecting the balance between mass loss due to basal melting and calving and mass gain due to snow accumulation is essential for understanding the Antarctic contribution to global sea level rise. Here, we investigate the climatological drivers of Antarctic SMB variability with a focus on the El Niño-Southern Oscillation (ENSO).

Snow accumulation in Antarctica is spatially and temporally variable, and accurate projections have been hampered by a paucity of long-term high-resolution observations (Frieler et al., 2015; Fox-Kemper et al., 2021; J.-Y. Lee et al., 2021). Three priorities for advancing research on the drivers of Antarctic accumulation change are:

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(a) understanding how large-scale atmospheric processes influence the SMB of the AIS; (b) understanding how Antarctic climate variability is connected to the mid-latitudes and tropics; and (c) determining the controls on regional patterns of Antarctic climate (Kennicutt et al., 2014, 2015). An improved characterization of how climate variability impacts Antarctic accumulation is important because regional accumulation increases, for example, in Dronning Maud Land in East Antarctica (Diener et al., 2021), have the potential to offset (on a continental scale) some of the projected ocean-driven mass losses in a warming climate (Fox-Kemper et al., 2021; Kittel et al., 2021; Seroussi et al., 2020).

There are several known climatological drivers of Antarctic surface climate, including the Southern Annular Mode (SAM) (Dätwyler et al., 2018; Fogt & Marshall, 2020; Medley & Thomas, 2019; Saunderson et al., 2024) and the Atlantic Multi-decadal Oscillation (Li et al., 2014, 2021). Here, we focus on ENSO, which is the leading mode globally of interannual climate variability, and exerts strong influences in Antarctica (Cullather et al., 1996; J. King & Turner, 1997; Ribera & Mann, 2003). El Niño impacts Antarctica by causing a weakening and shift in the location of the Amundsen Sea Low (ASL), through an atmospheric Rossby wave teleconnection (Kar-ameridou et al., 2020; Turner, 2004), with consequent changes in atmospheric circulation and precipitation patterns over Antarctica (Bodart & Bingham, 2019; Bromwich et al., 2004; Guo et al., 2004; Sun et al., 2013). El Niño events have also been shown to impact Antarctic temperature (T. Lee et al., 2010; Wilson et al., 2014), sea ice (C. Zhang, Li, & Li, 2021), surface melt (Clem et al., 2022), and ice shelf thickness (Paolo et al., 2018).

El Niño events fall into different types, defined by sea surface temperature (SST) anomalies in the tropical Pacific, with peak anomalies in either the central equatorial Pacific—denoted “CP El Niño”—or the eastern equatorial Pacific—denoted “EP El Niño”—(Ashok et al., 2007; Kug et al., 2009; Song et al., 2011). Distinct SST anomalies associated with CP and EP El Niño affect the location of maximum deep atmospheric convection in the tropical Pacific, causing the source location of Rossby wave trains to differ, occurring 20°–30° west during CP El Niño compared with EP El Niño (Chen et al., 2023; Clem et al., 2017; H.-J. Lee & Jin, 2021; C. Zhang, Li, & Li, 2021). This results in different Rossby wave propagation pathways to Antarctica resulting from CP and EP El Niño (Capotondi et al., 2015; Chen et al., 2023; Clem et al., 2017; H.-J. Lee & Jin, 2021; C. Zhang et al., 2021). C. Zhang, Li, and Li (2021) and Clem et al. (2017) show that the CP El Niño Rossby wave train results in a weakening and westward latitudinal shift in the ASL compared to EP El Niño.

Previous studies have identified ENSO signals in AIS SMB changes and elevation changes (Mémin et al., 2015; Kaitheri et al., 2021; Pfeiffer et al., 2022; Zhan et al., 2021; C. Zhang, Li, & Li, 2021). However, no studies to date have considered the impacts of different El Niño types on SMB in Antarctica (M. King et al., 2023; Sasgen et al., 2010). Here, we explore the temperature, precipitation and SMB changes over a 40-year period from 1979 to 2018 associated with different El Niño types (Figure S1 in Supporting Information S1).

2. Data Sets and Methods

2.1. Regional Climate Model Data: RACMO2.3p3

We assess climate variability over the Antarctic continent using output from the Regional Atmospheric Climate Model version 2.3p3 (RACMO2.3p3) (van Dalum et al., 2021, 2022). RACMO2.3p3 covers the Antarctic domain at 27 km resolution and is forced by 3-hourly global output from the European Center for Medium-Range Weather Forecasts atmospheric reanalysis (ERA5) for 1979–2018 (Hersbach et al., 2020; van Dalum et al., 2022). ERA5 is a global reanalysis, which assimilates observations and models to optimally produce data sets of global atmosphere, land surface and ocean variables since 1940 (Hersbach et al., 2020).

Antarctic surface elevation and drainage basins including catchment and regional names used in this study, are shown in Figure 1. We use monthly SMB, total precipitation and 2-m air temperature from RACMO2.3p3 for 1979–2018 (van Dalum et al., 2021, Figure S1 in Supporting Information S1). While 1979–1984 is considered a spin up period in RACMO2.3p3, we show that including or excluding the period 1979–1984 has little impact on our results (see Text S1, Figure S2–S3 in Supporting Information S1). This suggests that this spin-up period is still representative of Antarctic climatology and we therefore utilize the full 40-year output period in our study, as a longer period is beneficial for examining interannual variability. Seasonal averages are calculated over: December–February (DJF), March–May (MAM), June–August (JJA), and September–November (SON). This study focuses on austral winter (JJA) and austral spring (SON), when the ENSO–Antarctic teleconnection impacts

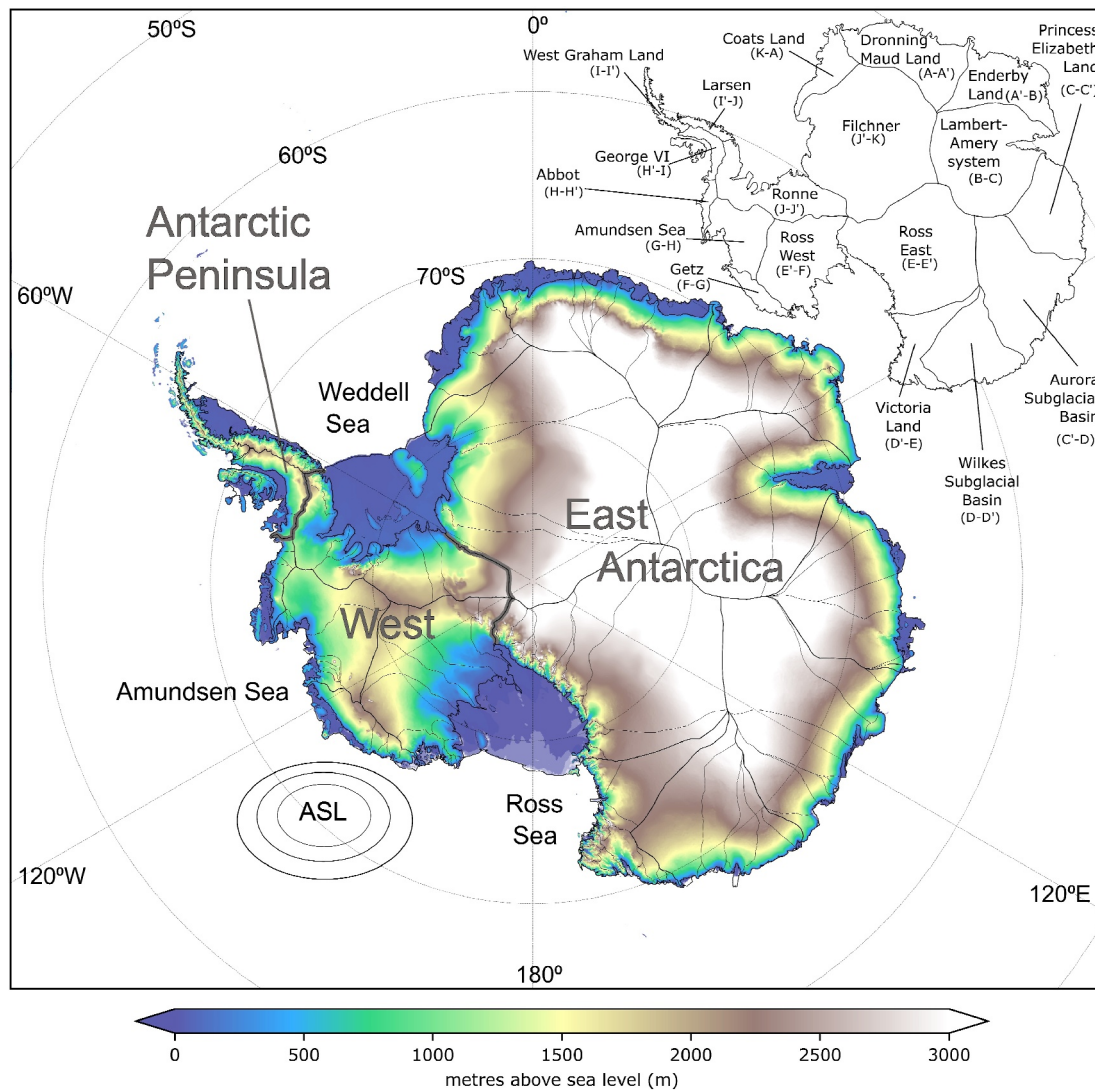


Figure 1. Antarctica surface elevation (contours; meters above sea level) from Liu et al. (2001), with individual drainage basins (thick black lines) and drainage basins subregions (thin black lines) from Rignot, Mouginot, and Scheuchl (2011) and Rignot, Velicogna, et al. (2011). Inset map with subregions defined by Rignot, Mouginot, and Scheuchl (2011). Amundsen Sea Low shown schematically.

are strongest and the ASL is located furthest southwest (Jin & Kirtman, 2009; Li et al., 2021; Renwick & Revell, 1999; Yiu & Maycock, 2020).

2.2. Reanalysis Data

We examine 0.25° resolution Mean Sea Level Pressure (MSLP) and 10-m wind vectors from ERA5 for the entire region south of 40°S (Hersbach et al., 2020). ERA5 covers a larger geographical extent than RACMO2.3p3, enabling analysis of atmospheric variables across the southern mid-latitudes (Hersbach et al., 2020; van Dalum et al., 2022). We use monthly and 3-month seasonal averages from 1979 to 2018 to match the period covered by RACMO2.3p3 data.

2.3. El Niño Indices

El Niño types are defined according to the location of peak SST anomalies in the tropical Pacific (Ashok et al., 2007; Kug et al., 2009). Central Pacific (CP) El Niño events and Eastern Pacific (EP) El Niño events are classified according to the Ren and Jin (2011) N_{CP} and N_{EP} indices respectively:

$$N_{EP} = N_3 - \alpha N_4 \quad (1)$$

$$N_{CP} = N_4 - \alpha N_3 \quad (2)$$

where

$$\alpha = \begin{cases} \frac{2}{5}, & N_3 N_4 > 0, \\ 0, & \text{otherwise.} \end{cases}$$

Here, N_3 is the Niño-3 index, which is the SST anomaly averaged over the regions 5°N–5°S and 150°–90°W, and N_4 is the Niño-4 index, which is the SST anomaly averaged over the regions 5°N–5°S and 160°E–150°W (Ren & Jin, 2011). Niño-3 and Niño-4 indices are sourced from NOAA (Rayner, 2003), based on the Hadley Center Sea Ice and Sea Surface Temperature data set (HadISST). We use 3-month seasonal averages from 1979 to 2018 of CP and EP El Niño indices (Equations 1 and 2). Between 1979 and 2018 five EP El Niño events (1982/83, 1991/92, 1997/98, 2006/07, 2015/16) and six CP El Niño events (1994/95, 2002/03, 2004/05, 2009/10, 2014/15, 2018/19) occur (extended data from Ren and Jin (2011)). We disregard the 1986/1988 El Niño event, which began as an EP El Niño but then matured into a CP El Niño (Ren & Jin, 2011). To maximize the length of the timeseries for our analysis, we exclude all negative values from each index (i.e., apply a threshold criterion of 0), which removes all La Niña (any flavor) years. This results in 22 CP El Niño data points and 15 EP El Niño events over the 40-year period.

2.4. Statistical Analyses

Power spectra are computed for total continental Antarctica, West Antarctica, and in the Antarctic Peninsula separately, using Welch overlapping segment averaging on mean detrended RACMO2.3p3 SMB, an over-sampling value of two, and a segment value of two (Mudelsee, 2010, see Text S2, Figure S4 in Supporting Information S1). Signal peaks at ~12, ~5.8, and ~2.4 years occur at the continental scale SMB (Figure S4a in Supporting Information S1), and at a regional scale in West Antarctica (Figure S4b in Supporting Information S1) and the Antarctic Peninsula (Figure S4c in Supporting Information S1), confirming that interannual variability dominates monthly Antarctic SMB.

We perform statistical analyses between Antarctic surface climate and different El Niño types. We do not perform Rossby wave dynamics analysis, as previous studies have established the changes associated with Rossby wave propagation to the southern high latitudes during CP and EP El Niño events (H.-J. Chen et al., 2023; Lee & Jin, 2021; Li et al., 2021). Here, we focus on statistical analyses between Antarctic surface climate and different El Niño types.

ENSO-Antarctic teleconnection impacts are strongest in JJA and SON when the subtropical jet is strongest, enabling the propagation of Rossby waves from the tropics to the poles; this is also when the ASL is shifted southwest (Jin & Kirtman, 2009; Li et al., 2021; Renwick & Revell, 1999; Yiu & Maycock, 2020). Therefore, we focus on JJA and SON results (Figures 2–4); other seasonal and lagged results are included in supplementary Figures S6–S9 in Supporting Information S1. We regress seasonal CP and EP El Niño indices (Equations 1 and 2) against seasonal 2-m air temperature, precipitation, SMB, MSLP and 10-m wind speed, relative to the 1979–2018 averages of these variables. This shows the seasonal changes in these variables associated with a 1°C strength CP or EP El Niño event, with tropical Pacific SST anomalies of 1°C (see Text S3 in Supporting Information S1, Figure 2). We also undertake composite analysis on seasonal CP and EP El Niño indices (Equations 1 and 2) against seasonal JJA and SON 2-m air temperature, precipitation, SMB, MSLP and 10-m wind speed for 1979–2018, to confirm robustness of regression results (see Text S4 in Supporting Information S1, Figures 3b, 3e–3f, 3i–3j, Figure S5 in Supporting Information S1). All fields are linearly detrended prior to calculating regressions and composites, to remove any long term trend over the timeseries. Statistical significance is established using a Students *t* test at the 5% confidence level. All results presented are statistically significant unless otherwise

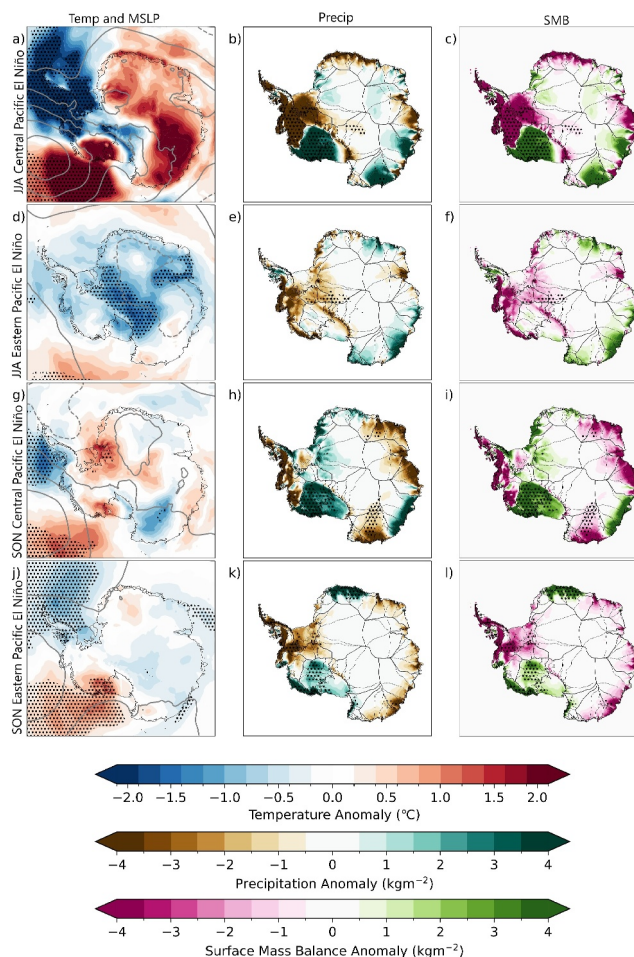


Figure 2. Modeled ENSO-Antarctic climate regressions in JJA (a–f) and SON (g–l): (a, d, g, j) 2-m air temperature (temp; from RACMO2.3p3) and mean sea level pressure (MSLP; gray; 2 hPa increments, (dashed lines are negative) from ERA5) (b, e, h, k) precipitation (Precip; from RACMO2.3p3), and (c, f, i, l) SMB (from RACMO2.3p3). Temperature, MSLP, precipitation and SMB anomalies represent seasonal changes in temperature, MSLP, precipitation and SMB when these variables are regressed against the JJA and SON CP or EP El Niño index relative to the 1979–2018 averages of these variables. These changes in temperature, MSLP, precipitation and SMB are associated with a 1°C strength CP and EP El Niño event when tropical Pacific SST anomalies are 1°C. Fields are linearly detrended prior to regressions onto the: N_{CP} index (first column, a, c, e) and N_{EP} index (second column, b, d, f) for 1979–2018 from Ren and Jin (2011) (methods). Stippling indicates statistical significance at the 5% confidence level using a two-tailed Students' t test.

indicated. Auto-correlation is accounted for by utilizing seasonal averages (Mudelsee, 2010, see Text S5 in Supporting Information S1).

3. Results

3.1. CP and EP El Niño Impacts on Regional Climate and SMB

3.1.1. CP El Niño

Figure 2 shows the seasonal changes in temperature, MSLP, precipitation and SMB when these variables are regressed against the JJA and SON CP or EP El Niño index relative to the 1979–2018 averages of these variables. These anomalies show changes in temperature, MSLP, precipitation and SMB which are associated with a 1°C strength CP and EP El Niño event when tropical Pacific SST anomalies are 1°C. During CP El Niño, in both JJA

and SON, positive temperature anomalies are widespread across the Amundsen and Ross Seas, and negative anomalies persist across the Antarctic Peninsula (Figures 1 and 2a, Figure S5a in Supporting Information S1). We refer to these spatial patterns as “dipoles” (Figure 2a). In JJA negative temperature anomalies also occur across the Weddell Sea (Figures 1 and 2a) whilst in SON, positive temperature anomalies occur in the Weddell Sea and Ronne-Filchner catchment (Figure 2g, Figure S5g in Supporting Information S1).

A dipole pattern also occurs in precipitation and SMB anomalies during CP El Niño in JJA, with increases in the Ross West sector and decreases across the Amundsen Sea sector (Figures 2b and 2c, 2h and 2i). During SON similar precipitation and SMB increases occur in the Ross West sector, but decreases across the Amundsen Sea sector are not significant (Figures 2h and 2i, Figures S5h and S5i in Supporting Information S1).

3.1.2. EP El Niño

During EP El Niño, there is decreased temperature in JJA across West Antarctica relative to CP El Niño, but there is no significant temperature change over the Peninsula (Figure 2d, Figure S5d in Supporting Information S1). In SON, during EP El Niño, a positive temperature anomaly occurs across the Amundsen and Ross Sea sectors, whilst a negative temperature anomaly extends over both the Antarctic Peninsula and Weddell Sea (Figure 2j). Temperature anomalies in West Antarctica during EP El Niño in SON are similar to those during CP El Niño in JJA and SON (Figures 2a, 2g, and 2j, Figure S5j in Supporting Information S1).

The magnitude of the anomalies in atmospheric circulation and thus in the resulting precipitation and SMB is lower during EP El Niño than CP El Niño—highlighting that CP El Niño has a much greater impact on Antarctic SMB than EP El Niño (Figures 2a–2f). In contrast with CP El Niño, EP El Niño events have very little impact on precipitation and SMB fields during JJA (Figures 2e and 2f). However, during SON, there are increases in precipitation and SMB in the Ross West basin and decreases in precipitation and SMB in the Peninsula and Amundsen Sea region during EP El Niño events—a similar pattern to the changes occurring during CP El Niño events, but of a lesser magnitude and less widespread (Figures 2h and 2i, 2k and 2l).

In summary, our results reveal distinctly different spatial signatures in atmospheric variables and SMB during CP and EP El Niño events, with larger magnitude and more widespread changes occurring during CP El Niño compared to EP El Niño (Figure 2, Figure S5 in Supporting Information S1). Furthermore, we show different spatial CP and EP El Niño impacts in JJA and SON, revealing that CP and EP El Niño do not have the same teleconnective impacts during the same seasons (Figures 2 and 3, Figure S5 in Supporting Information S1). Strong teleconnective relationships occur between the tropical Pacific and Antarctica during both JJA and SON, and weaker relationships occur during DJF and MAM (Figure 2, Figures S6 and S7 in Supporting Information S1). East Antarctic impacts generally differ between drainage basins and are mostly not statistically significant; see Texts S6–S7 in Supporting Information S1 for further discussion of the East Antarctic impacts.

3.2. Atmospheric Drivers of El Niño SMB Impacts in West Antarctica

During CP El Niño, positive MSLP changes occur over the West Antarctic coastline in the Amundsen Sea, with a consequent weakening and westwards shift in the ASL (Figures 3c–3f). This results in strong easterly, moisture-laden onshore winds flowing into West Antarctica from the Ross Sea sector (Figures S13a, S13c, S13e, and S13g in Supporting Information S1). Orographic uplift results in precipitation increases in the region (Figures 2b and 2h), which drive SMB gain (Figures 3a–3f). Simultaneously, over the Amundsen Sea sector and the Antarctic Peninsula, downslope winds (Figures S13a, S13c, S13e, and S13g in Supporting Information S1) are associated with reduced precipitation and SMB decreases (Figures 3a–3f).

The ASL only slightly weakens during EP El Niño events compared with CP events, with the center remaining close to the seasonal mean state location during JJA and shifting slightly east during SON (Figures 3g–3j). However, during EP El Niño in JJA, easterly winds flowing across West Antarctica are sourced from the continent, not the ASL (Figures S13b and S13d in Supporting Information S1). This results in a reduced impact on Antarctic precipitation and SMB gain as these winds are not moisture-laden (Figures 3g and 3i).

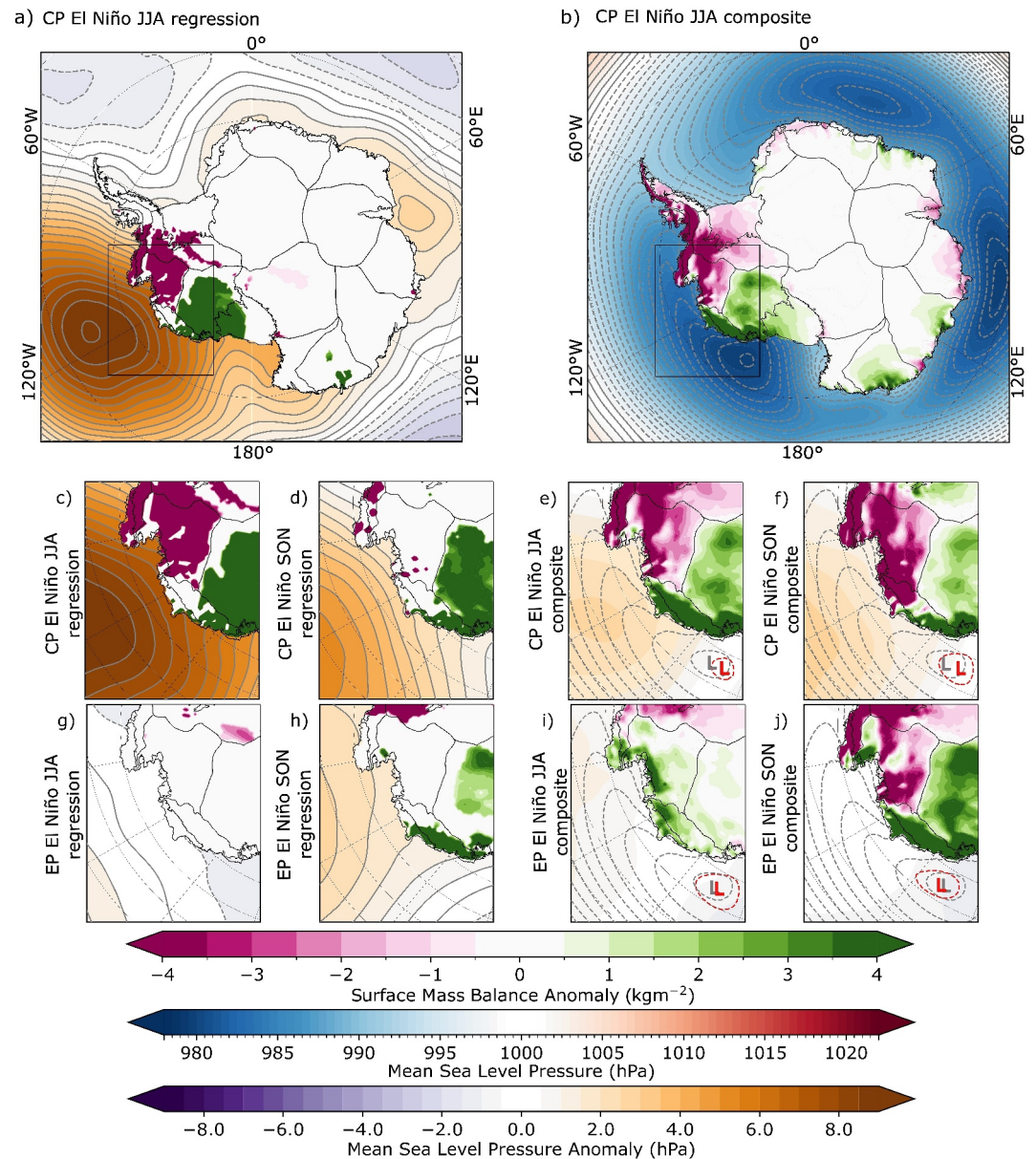


Figure 3. Regression (a, c, d, g, h) and composite (b, e, f, i, j) SMB (from RACMO2.3p3) and Antarctic atmospheric circulation (from ERA5) during CP JJA El Niño (a–c, e); EP JJA El Niño (g, i); CP SON El Niño (d, f); and EP SON El Niño (h, j). Pink (negative)-green (positive) shading indicates SMB regression (a, c, d, g, h) and composite (b, e, f, i, j) anomalies relative to the 1979–2018 averages for these variables. Purple (negative)-orange (positive) shading indicates MSLP regression (a, c, d, g, h) and composite (e, f, i, j) anomalies at 0.25 hPa increments. (b) Blue-red shading indicates average JJA total MSLP (hPa; from ERA5) and gray lines (dashed) indicate composite total MSLP for CP JJA El Niño above (and below) 1000 hPa. (e, f, i, j) Average seasonal composite “mean state” MSLP above 1000 hPa (gray lines, dashed below 1000 hPa). Red line indicates location of ASL center during (e) CP JJA, (f) CP SON, (i) EP JJA, and (j) EP SON. Composite MSLP anomalies are calculated by subtracting the average seasonal “mean state” MSLP (composite of all years 1979–2018) (gray lines) from the total MSLP (red line) composite during (e) CP JJA, (f) CP SON, (i) EP JJA, and (j) EP SON. All results shown are statistically significant at the 5% confidence level using a two-tailed Students' *t* test.

4. Discussion and Conclusions

We compare the regional differences in RACMO SMB (during JJA and SON) in response to CP and EP El Niño over the period 1979–2018. CP and EP El Niño have distinctly different impacts due to changes in teleconnections that lead to shifts in the position and strength of the ASL, and consequent changes in regions influenced by these El Niño types (Chen et al., 2023; H.-J. Lee & Jin, 2021; C. Zhang et al., 2021; Figure 3).

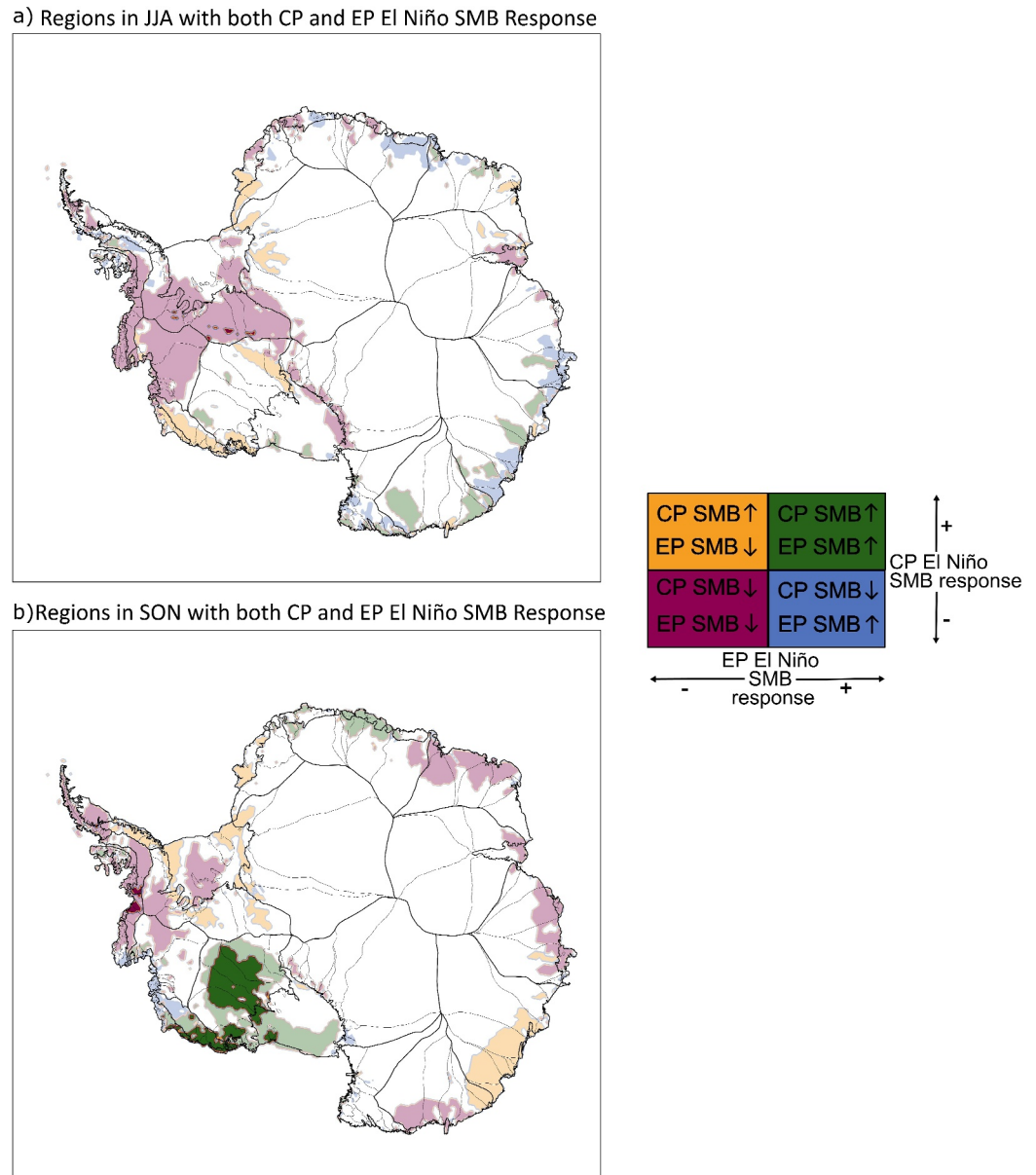


Figure 4. Impact of different El Niño types on SMB in JJA (a) and SON (b). Regions which respond to both El Niño types with SMB increase (green), SMB decrease (pink), limited response (white; i.e., $-1 \leq x \leq 1 \text{ kg/m}^2$). Regions with opposing SMB responses (orange (CP increase, EP decrease) and blue (CP decrease, EP increase)). See Figures S14 and S15 in Supporting Information S1 for regions which respond to one El Niño type. Regions that are not statistically significant at the 5% confidence level using a two-tailed Student's *t* test are shown with 65% transparency.

We summarize the different impacts of CP and EP El Niño in JJA and SON on SMB in Figure 4 (Figures S14 and S15 in Supporting Information S1 for regions that only show responses to one El Niño type). The largest impacts of EP and CP-related El Niño events on Antarctic SMB are evident in coastal zones and large parts of West Antarctica (Figure 4, Figure S14 in Supporting Information S1); however, there is significant variability in SMB in most coastal regions, which leads to a different magnitude and sign of SMB changes depending on the El Niño type and season. This variability is associated with changes in circulation, and upslope and downslope winds during the different ENSO types (Figures 1 and 3, Figure S13 in Supporting Information S1). Several regions—including parts of the Ross West and Dronning Maud Land regions and Wilkes Subglacial Basin—show strong SMB responses solely during one El Niño type (Figures S14b–S14c, S15b–S15c in Supporting Information S1).

Previous analyses of the climatic response of Antarctica to ENSO forcing include impacts on southern high latitude atmospheric circulation (Ciaasto et al., 2015; J.-Y. Lee et al., 2021; Sun et al., 2013; Wilson et al., 2014). Our findings are consistent with these studies, with changes in the strength and location of the ASL being well-established (Chen et al., 2023; Clem et al., 2017; H.-J. Lee & Jin, 2021; C. Zhang et al., 2021). The precipitation and accumulation changes we identify here are also in agreement with other studies which identify ENSO-forced Antarctic precipitation changes, driven by anomalous circulation bringing warm, moisture-laden air over the continent (Chen et al., 2023; Cullather et al., 1996; Paolo et al., 2018; Sasgen et al., 2010). Only some of these studies consider how different El Niño types influence Antarctic surface climate (specifically temperature changes associated with large-scale circulation); however, none of these studies consider how different El Niño types influence Antarctic SMB (Chen et al., 2023; Cullather et al., 1996; Paolo et al., 2018; Sasgen et al., 2010). EP El Niño tropical SST anomalies are generally larger than CP El Niño tropical SST anomalies (Figures S1d and S1e in Supporting Information S1), which has led to previous studies conventionally considering the EP El Niño associated atmospheric response to be stronger than CP (Chen et al., 2023; Sun et al., 2013; Wilson et al., 2014). By contrast, our findings show CP El Niño in JJA induces larger Antarctic SMB changes than EP El Niño (Figures 2a–2f) and CP and EP El Niño in SON induce similar Antarctic SMB changes (Figures 2g–2l).

Our findings are consistent with previous analyses of the impacts of ENSO forcing on Antarctic temperature (Clem et al., 2018; Ding & Steig, 2013; Li et al., 2014, 2015, 2021; B. Zhang et al., 2021). Previous studies have demonstrated that temperature decreases in the Antarctic Peninsula and increases in the East Antarctic and western Ross region are associated with El Niño (e.g., Li et al. (2014, 2015, 2021)). Our findings generally support those summarized in Li et al. (2021). However, by isolating CP and EP El Niño-driven impacts on temperature, our results suggest that the temperature changes synthesized in Li et al. (2021) align more closely to CP El Niño-driven changes rather than EP El Niño-driven changes. We also identify larger magnitude temperature anomalies during CP El Niño in JJA from regression analysis (not all significant) than from composite results (significant) (Figure 2a, Figure S5 in Supporting Information S1). In other words, previous studies (Kaitheri et al., 2021; King et al., 2023; Mémin et al., 2015; Paolo et al., 2018; M. Sasgen et al., 2010) may be underestimating the impact of El Niño on Antarctic SMB; regions may be exhibiting opposing responses to each El Niño type, effectively canceling out some of the impacts when ENSO diversity is not accounted for (Figure 4). Our results make clear the need to consider spatial variability in El Niño type to fully understand Antarctic climate impacts (van Dalum et al., 2022; Figure 3). For example, the integrated SMB change over the Ross West sector is approximately 4 kg/m² during both CP and EP ENSO events (Figure 3), which represents 10% of the seasonal SMB change in this region (van Dalum et al., 2021).

Our analysis is limited by a short data window (Text S8 in Supporting Information S1). The 40-year analysis period of this study (1979–2018) is the temporal extent of the RACMO2.3p3 data set. This 40-year record is not long enough to investigate decadal signals (Figure S4 in Supporting Information S1), therefore we focus on interannual variability. However, this 40-year timeseries is unlikely to capture the full range of variability expected in ENSO, which has been estimated to require 100–200 years timeseries length (Stevenson et al., 2010; Wittenberg, 2009). Furthermore, the 40-year period that we analyze likely includes impacts from both natural climate variability and anthropogenic forcings, between which we are unable to distinguish (Fox-Kemper et al., 2021; Meredith et al., 2019). Therefore, our results might not be representative of the full range of Antarctic climate impacts associated with El Niño spatial variability. Future work utilizing climate models and palaeoclimate data have the potential to better explain the CP and EP El Niño relationships with SMB.

Our results show the fundamental role that climate variability plays in Antarctic SMB. We highlight the need to consider how modes of variability such as ENSO will change with climate change, and impact Antarctic SMB. Projections of future ENSO characteristics remain uncertain (Fox-Kemper et al., 2021). Some CMIP6 ensemble results suggest a consensus on ENSO changes, projecting increased intensity and frequency of El Niño events (Cai et al., 2014, 2021; Shin et al., 2022). If these projections and teleconnections hold, our results suggest that greater changes in Antarctic SMB could occur with both El Niño types (Figure 2). The Freund et al. (2019) reconstruction of CP El Niño shows an increase in frequency over the 20th Century compared to the previous 400 years. If this increased frequency of CP El Niño events continues, as Shin et al. (2022) projects, our results suggest there may be significant Antarctic SMB impacts (Figures 2 and 3). Therefore, understanding future projections of El Niño, including changes in frequency, intensity, and specifically El Niño type is crucial for accurately predicting Antarctic SMB changes.

Data Availability Statement

All data sets are freely available. Regional Atmospheric Climate Model version 2.3 polar version 3 2-m temperature, precipitation, surface mass balance and melt are available at van Dalum et al. (2021) (<https://doi.org/10.5281/zenodo.7639053>). ERA5 reanalyses data including mean sea level pressure and 10-m wind vectors are available at Hersbach et al. (2020) (<https://doi.org/10.1002/qj.3803>). El Niño indices, Niño-3 and Niño-4 are available at Rayner (2003) (<https://doi.org/10.1029/2002JD002670>).

Acknowledgments

AM, ANM, FSM, AP, HVM and BJH were supported by the Australian Research Council Special Research Initiative for Securing Antarctica's Environmental Future (SR200100005). JMAM was supported by the Monash Graduate Scholarship (MGS) and Monash International Tuition Scholarship (MITS). FSM was supported under an Australian Research Council Discovery Early Career Research Award (DE210101433). CTVD was supported under Horizon 2020 (PROTECT grant no.869304). Open access publishing facilitated by Monash University, as part of the Wiley - Monash University agreement via the Council of Australian University Librarians.

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