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*Supplement of*

# How do extreme ENSO events affect Antarctic surface mass balance?

**Jessica M. A. Macha et al.**

*Correspondence to:* Jessica M. A. Macha (jessica.macha@monash.edu)

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## Introduction

This supporting information provides supplementary figures, tables and text to the main manuscript of *How do extreme ENSO events affect Antarctic surface mass balance?*

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## S1. Regional Climate Model RACMO2.3p3

### Text S1.

In this study we utilise RACMO2.3p3, a hydrostatic model developed specifically for use over the polar regions (Carter et al. 2022; van Dalum et al. 2022). RACMO2.3p3 is the updated version of RACMO2.3p2, and includes an updated spectral snow and ice albedo scheme and an updated multi-layer firn module (van Dalum et al. 2022). Surface climate variables in RACMO2.3p3, including SMB, energy balance, surface melt, temperature, albedo and snow grain, have been shown to compare well with both RACMO2.2p2 variables (van Dalum et al. 2022). RACMO also compares well with *in situ* and remotely sensed data, and other ice sheet model results (van Dalum et al. 2022; Noël et al. 2023; Kappelsberger et al. 2024). Unlike other regional climate models adapted to the Antarctic domain, RACMO2.3p3 represents the insulating properties in the snow column, by including a multi-layer firn module, whilst other models such as the MetUM comparatively utilise a zero-layer snow/soil composite module (Carter et al. 2022; van Dalum et al. 2022).

RACMO2.3p3 couples the High Resolution Limited Area Model version 5.0.3 (HIRLAM) atmospheric dynamics with the European Centre for medium-Range Weather Forecasts (ECMWF) Integrated Forecast System atmospheric and surface physics, using cycle 33r1 (ECMWF 2009). In RACMO2.3p3 dry snow metamorphism is calculated using Snow, Ice, and Aerosol Radiation Model, an important component of calculating SMB (Flanner and Zender 2006; Gelman Constantin et al. 2020). RACMO2.3p3 is coupled to the Two-streAm Radiative TransfEr in Snow model (TARTES) through the Spectral-to-Narrow Band Albedo (SNOWBAL) module version 1.2, which allows sub-surface heating and sub-surface melting in the model, both important parts of the ice sheet mass balance and dynamics (Libois et al. 2013). Precipitation is also an important part of SMB calculations in RACMO2.3p3, with fine-scale snow processes and post-depositional accumulation processes included in RACMO enabling accurate estimates of SMB in Antarctica (Carter et al. 2022; Nicola et al. 2023; Noël et al. 2023; Seroussi et al. 2023). For these reasons we utilise RACMO2.3p3 near-surface temperature, precipitation and surface mass balance output in our study, as these are adapted to the Antarctic Ice Sheet. ERA5 provides coarser resolution of atmospheric variables which drive RACMO2.3p3 atmospheric circulation boundaries and provide insight into the wider atmospheric circulation anomalies outside the RACMO Antarctic domain (Hersbach et al., 2020). ERA5 also does not include a firn module, making its output not as appropriate to address the aims of this study.

## S2. Classifying Central Pacific and Eastern Pacific El Niño indices

**Text S2.**

Central Pacific (CP) El Niño events and Eastern Pacific (EP) El Niño events are classified in the same way as Macha et al. (2024) according to the Ren and Jin (2011) $N_{CP}$ and $N_{EP}$ indices respectively:

$$N_{EP} = N_3 - \propto N_4 \quad \text{(S1)}$$

$$N_{CP} = N_4 - \propto N_3 \quad \text{(S2)}$$

Where:

$$\propto = \begin{cases} \frac{2}{5} N_3 N_4 > 0, \\ 0, otherwise \end{cases}$$

Here, $N_3$ is the Niño-3 index, which is the SST anomaly averaged over the regions 5ºN--5ºS and 150º-90ºW, and $N_4$ is the Niño-4 index, which is the SST anomaly averaged over the regions 5ºN--5ºS and 160ºE--150ºW (Ren and Jin 2011). Niño-3 and Niño-4 indices are sourced from NOAA (Rayner 2003), based on the HadISST dataset. We use 3-month seasonal averages from 1979--2018 CP and EP El Niño indices (Equations 1; 2).

## S3. Calculating Outliers

**Text S3.**

We identify outliers in each regional cumulative SON SMB anomaly dataset using Equations S1-S3 (Mudelsee 2010) for Figure 5.

$$IQR = Q3 - Q1 \quad \text{(S3)}$$

$$Upper\ Outlier\ Bound = Q3 + 1.5\ IQR \quad \text{(S4)}$$

$$Lower\ Outlier\ Bound = Q1 - 1.5\ IQR \quad \text{(S5)}$$

where:

$Q1 = lower\ quartile\ (25th\ percentile)$

$Q3 = upper\ quartile\ (75th\ percentile)$

## S4. Rossby wave analysis

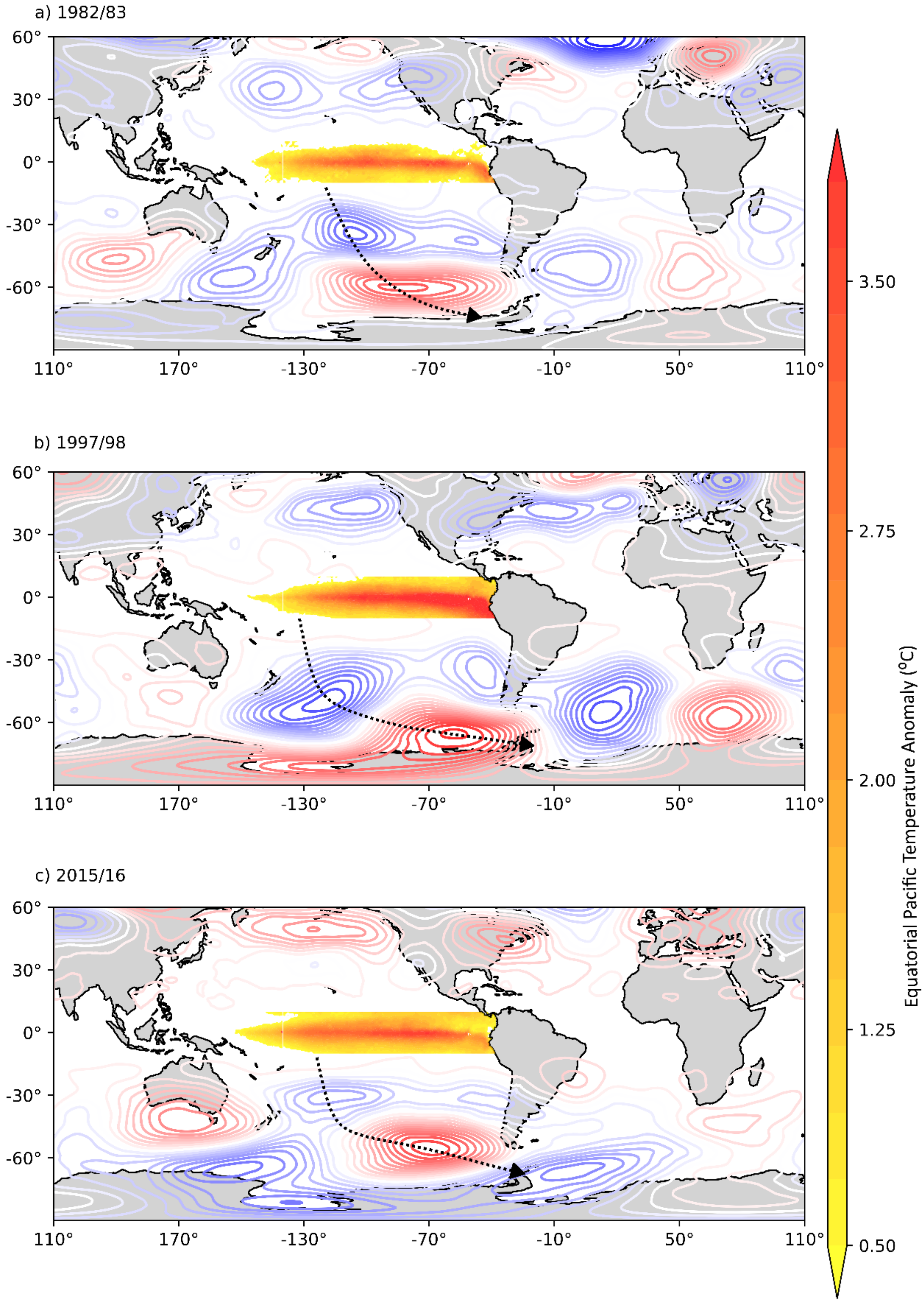



**Figure S1.** Tropical-Polar teleconnections during extreme El Niño events. Austral Spring (SON) 500-hPa geopotential height anomalies (contours) during each extreme El Niño event (a) 1982/83, (b) 1997/98, (c) 2015/16, and associated equatorial Pacific warming (colour shading, bar) with arrows showing Rossby wave propagation schematically.

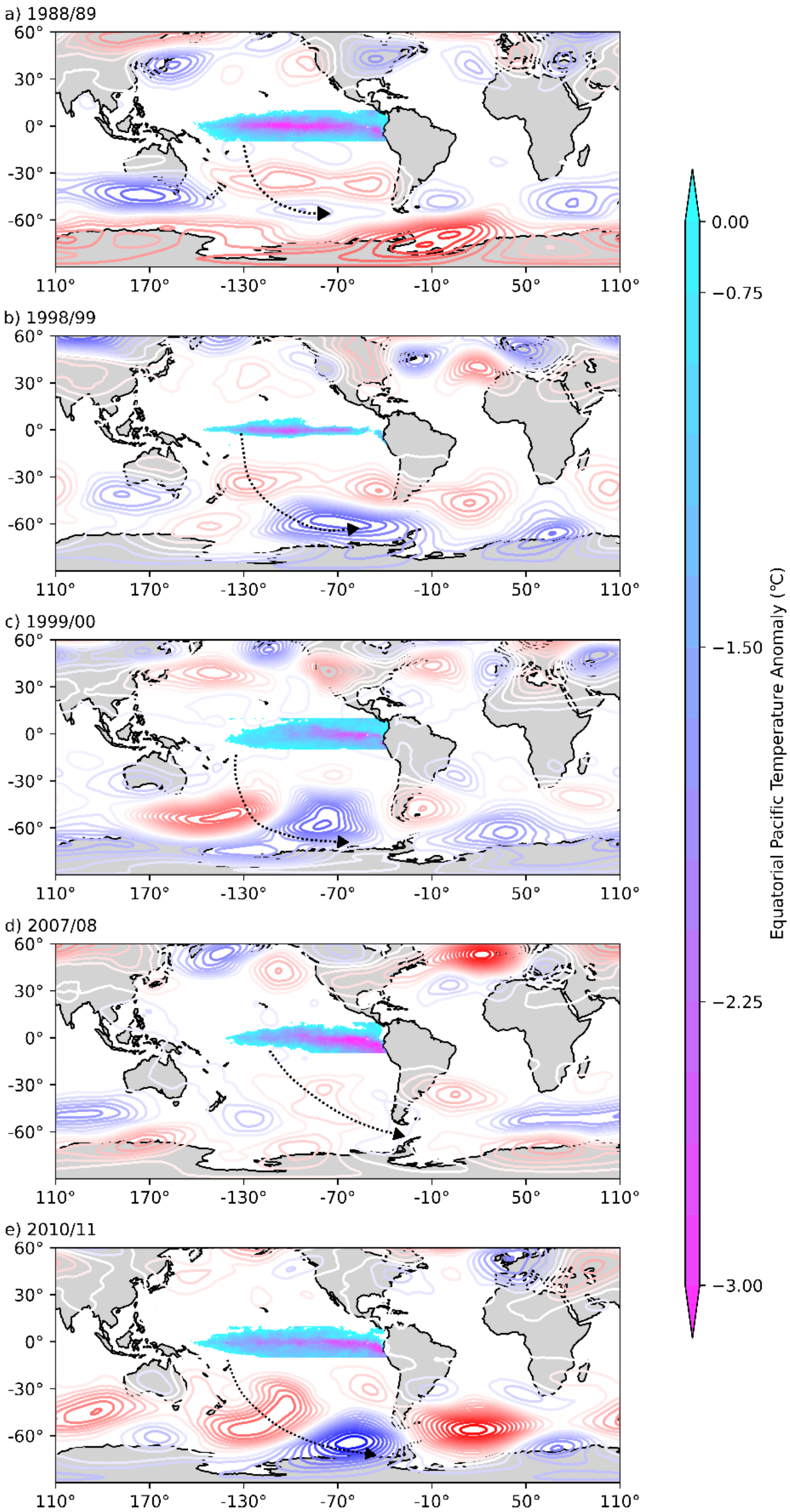
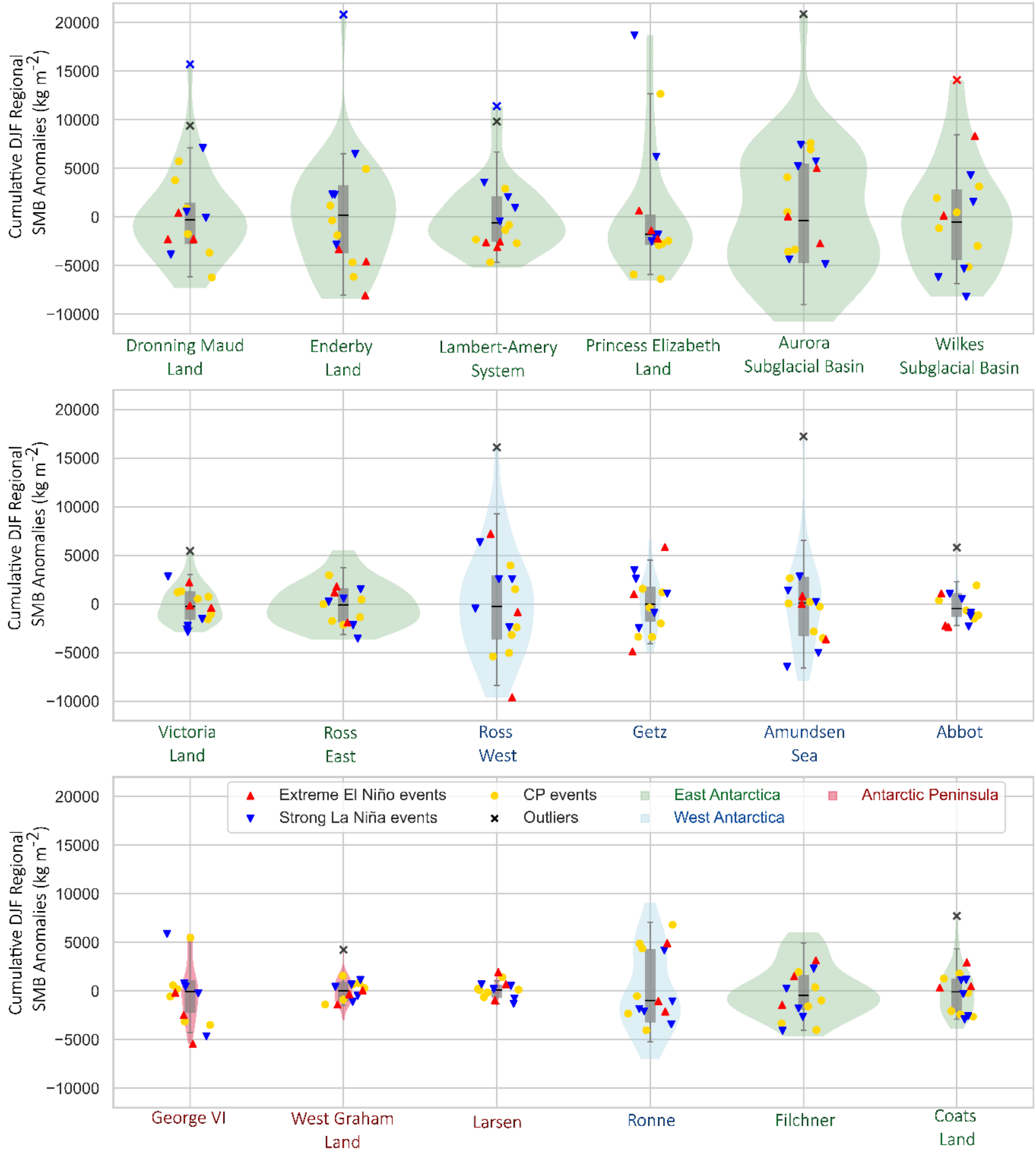



**Figure S2.** Tropical-Polar teleconnections during strong La Niña events. Austral Spring (SON) 500-hPa geopotential height anomalies (contours) during each extreme El Niño event (a) 1988/89, (b) 1998/99, (c) 1999/00, (d) 2007/08, (e) 2010/11, and associated equatorial Pacific cooling (colour shading, bar) with arrows showing Rossby wave propagation schematically.

**Text S4:**

Rossby wave analysis of the austral spring (SON) 500-hPa geopotential height anomalies across the southern hemisphere is undertaken during each extreme ENSO event analysed (Supplementary Figures S1-S2). This analysis allows the teleconnection between the tropics and the poles to be visualised during each extreme ENSO event, as the propagation pathway is highlighted. This analysis also allows the differences in this propagation between individual extreme ENSO events to be compared. During each El Niño event we note differences in where the Rossby wave train extends over the Antarctic continent, with the wave train extending further east during the 2015/16 event than the 1982/83 and 1997/98 events (Supplementary Figure S1). We also note a more consistent Rossby wave train occurs during each extreme El Niño event, compared to the wave train during each strong La Niña event (Supplementary Figure S1-S2). The Rossby wave analysis shows that the wave trains during strong La Niña events show greater variability (Supplementary Figure S1-S2). However, the Rossby wave analysis shown here does not allow the full range of mechanisms underpinning our results to be revealed because ENSO-driven Rossby wave trains cannot be easily isolated from local, short term and regional atmospheric circulation and climate changes in the southern midlatitudes (Renwick and Revell 1999; Clem et al. 2018; Yiu and Maycock 2020; McGregor et al. 2022).

153 ## S5. Violin plots of SMB




154

155 **Figure S3. Relationship between extreme ENSO events and regional Antarctic surface**
156 **mass balance anomalies during DJF**. Density curves of regional cumulative DJF SMB
157 anomalies for each Antarctic Ice Sheet regional catchment (a-j), scaled by the regional
158 catchment size. Box plots show the interquartile range (IQR), with medians (black line) and
159 whiskers (5th and 95th percentiles). East Antarctic (light green), West Antarctic (light blue)
160 and Antarctic Peninsula (pink) catchments, outliers (crosses; see supplement), extreme El
161 Niño events (red), strong La Niña events (blue) and Central Pacific El Niño events (yellow)
162 are highlighted.

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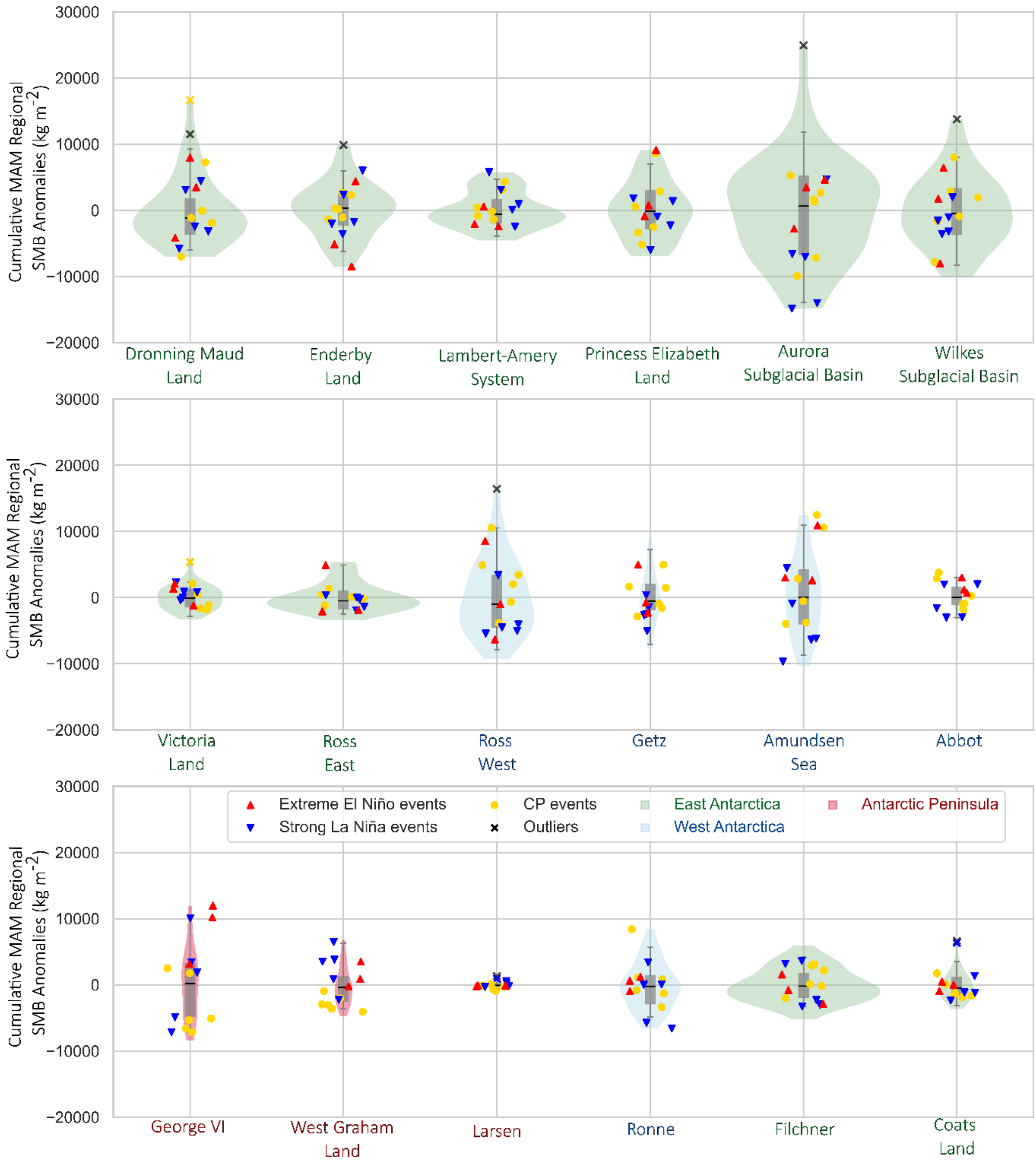


**Figure S4. Relationship between extreme ENSO events and regional Antarctic surface mass balance anomalies during MAM.** Density curves of regional cumulative MAM SMB anomalies for each Antarctic Ice Sheet regional catchment (a-j), scaled by the regional catchment size. Box plots show the interquartile range (IQR), with medians (black line) and whiskers (5th and 95th percentiles). East Antarctic (light green), West Antarctic (light blue) and Antarctic Peninsula (pink) catchments, outliers (crosses; see supplement), extreme El Niño events (red), strong La Niña events (blue) and Central Pacific El Niño events (yellow) are highlighted.

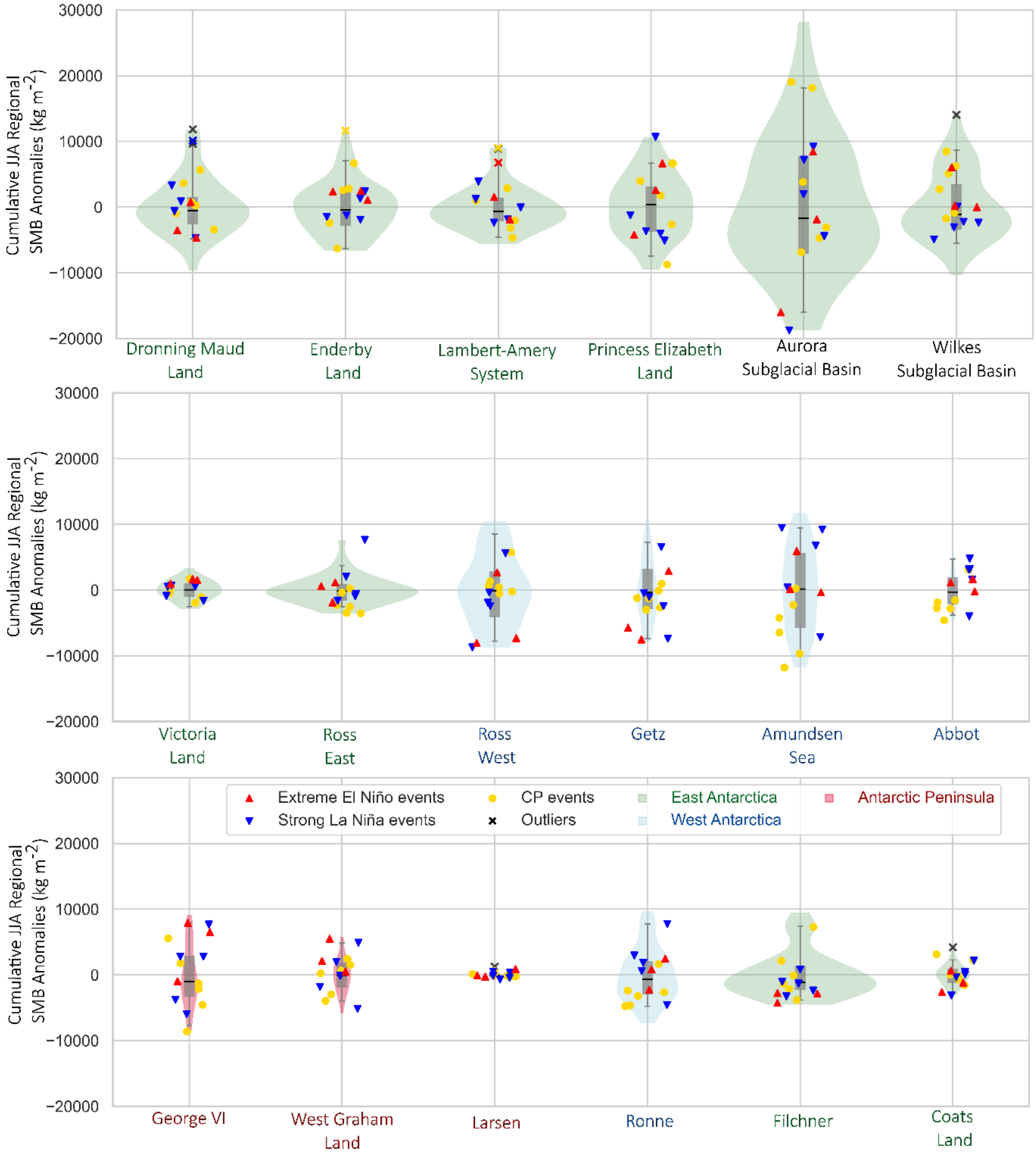


**Figure S5. Relationship between extreme ENSO events and regional Antarctic surface mass balance anomalies during JJA**. Density curves of regional cumulative JJA SMB anomalies for each Antarctic Ice Sheet regional catchment (a-j), scaled by the regional catchment size. Box plots show the interquartile range (IQR), with medians (black line) and whiskers (5th and 95th percentiles). East Antarctic (light green), West Antarctic (light blue) and Antarctic Peninsula (pink) catchments, outliers (crosses; see supplement), extreme El Niño events (red), strong La Niña events (blue) and Central Pacific El Niño events (yellow) are highlighted.

**Text S5.**

Supplementary Figures S1-S3 show DJF, MAM and JJA results. These figures show the relationship between extreme ENSO events and regional Antarctic surface mass balance anomalies on a seasonal scale, as they show the SMB anomaly distributions for each Antarctic catchment with each extreme ENSO event highlighted. SMB responses during extreme ENSO events and all seasons are not consistent in East Antarctica, West Antarctica or the Antarctic Peninsula (Supplementary Figure S1-S3).

During DJF, SMB responses vary between events (Supplementary Figure S3). However, during extreme El Niño events SMB anomalies are consistently negative in Enderby Land and the Lambert-Amery System (Supplementary Figure S3). Large positive cumulative SMB anomalies are also identified during austral summer for different strong La Niña events in Dronning Maud Land (2010/11), Enderby Land (1988/89), the Lambert-Amery System (1999/2000) and Princess Elizabeth Land (2007/08; Supplementary Figure S3). During MAM, no consistent SMB responses are identified during extreme El Niño events, strong La Niña events or CP El Niño events (Supplementary Figure S4). During JJA, SMB responses across Antarctica are generally inconsistent during extreme ENSO events, other than in Enderby Land and Lambert-Amery System during CP El Niño events where positive SMB anomalies are identified as outliers (Supplementary Figure S5).

## S6. Scatter plots of SMB

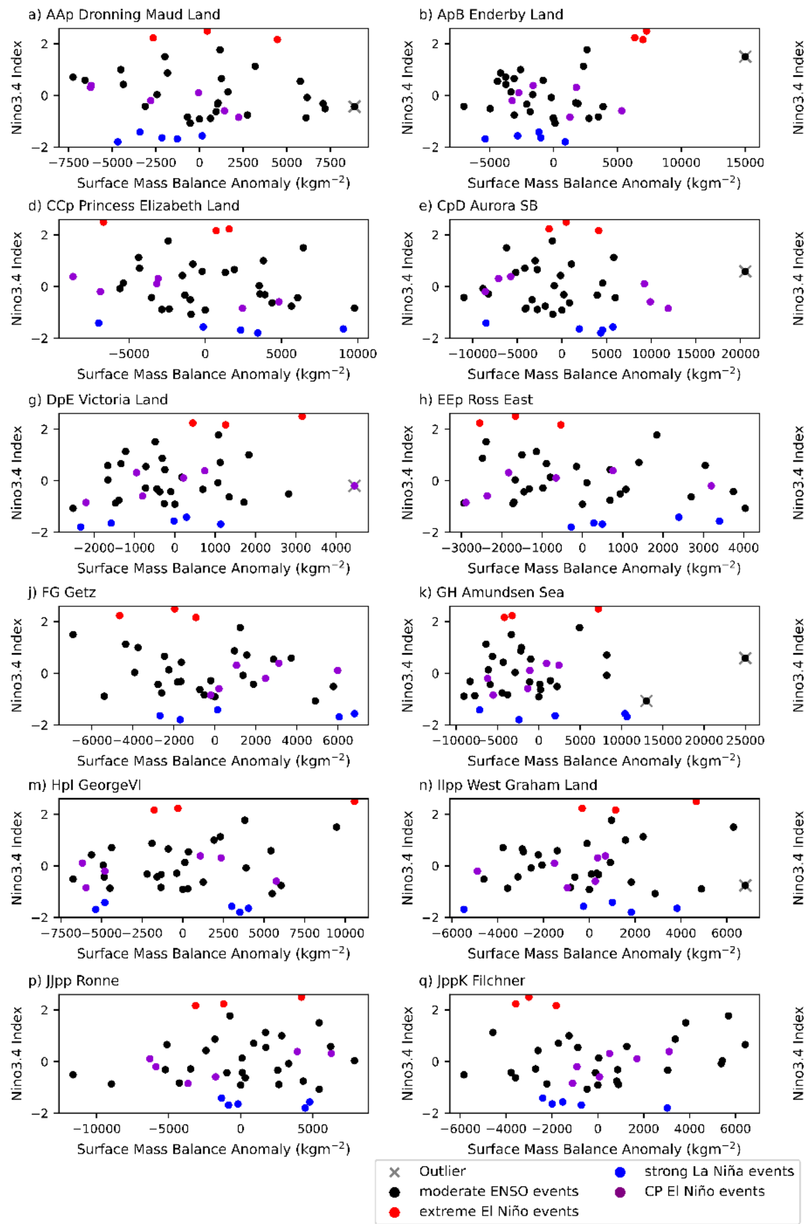


**Figure S6.** Scatter plots of regional cumulative SON surface mass balance anomaly from 1979-2018 against the Niño3.4 Index across all Antarctic Ice Sheet regional basins (a-r). No trendlines are included as no trendline is statistically significant at the 5% confidence level using a two-tailed Students' *t* test. Outliers (grey cross), moderate ENSO events (black), extreme El Niño events (red), strong La Niña events (blue) and Central Pacific El Niño events (purple).

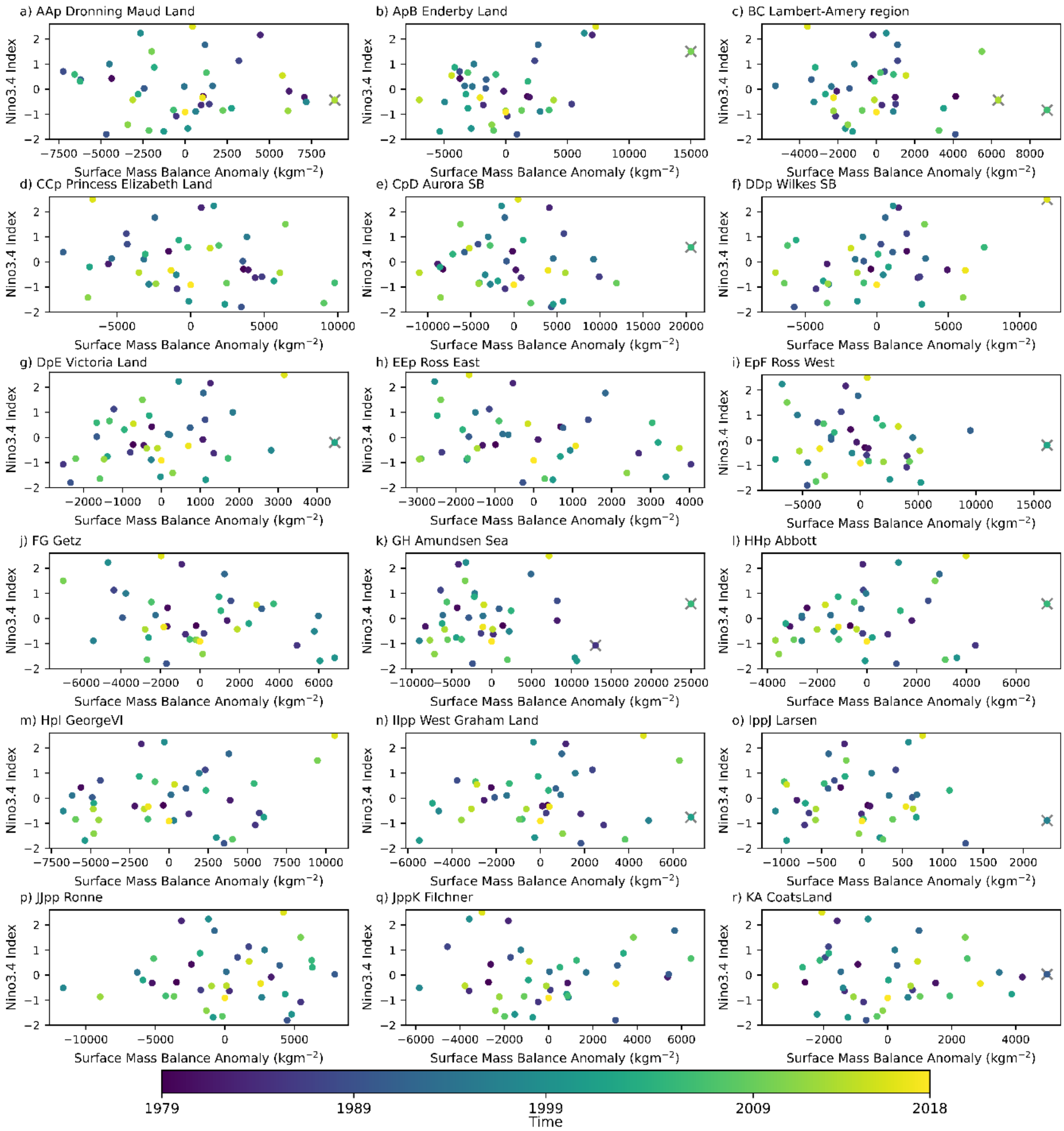


**Figure S7.** Scatter plots of regional cumulative SON surface mass balance anomaly from 1979-2018 against the Niňo3.4 Index across Antarctic Ice Sheet regional basins (a-r), coloured according to year (colour bar).

## S7: Regional SMB histograms during extreme El Niño events

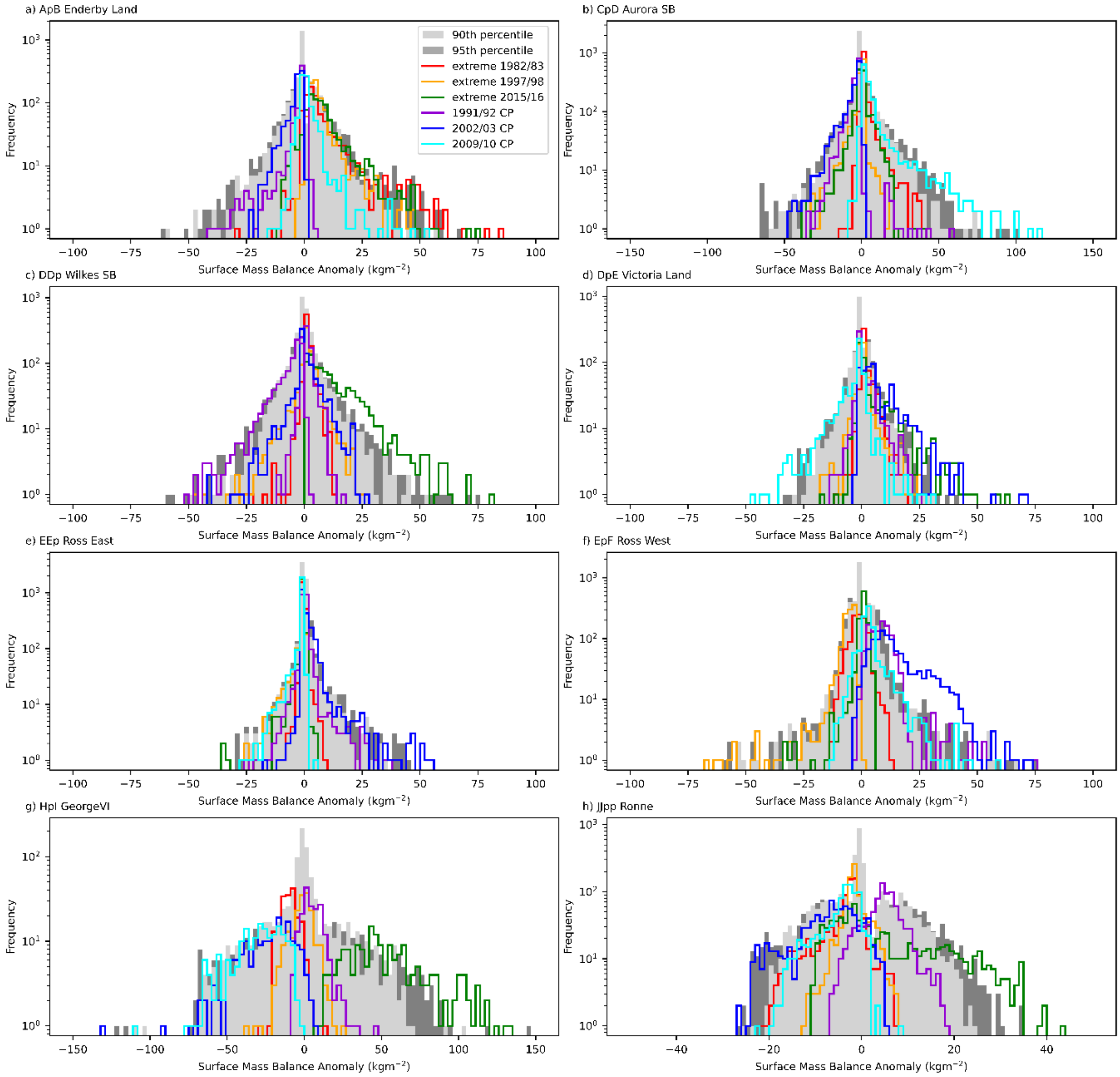


**Figure S8. Probability distributions of regional Antarctic surface mass balance anomalies during extreme El Niño events and CP El Niño events.** Regional SMB probability distributions of SMB anomalies in SON for extreme El Niño events: 1982/83 (red), 1997/98 (orange) and 2015/16 (green); and CP El Niño events: 1991/92 (purple), 2002/03 (blue) and 2009/10 (cyan). Regional 90th (light grey shading) and 95th percentile (dark grey shading) SMB anomalies for SON for 1979-2018 period.

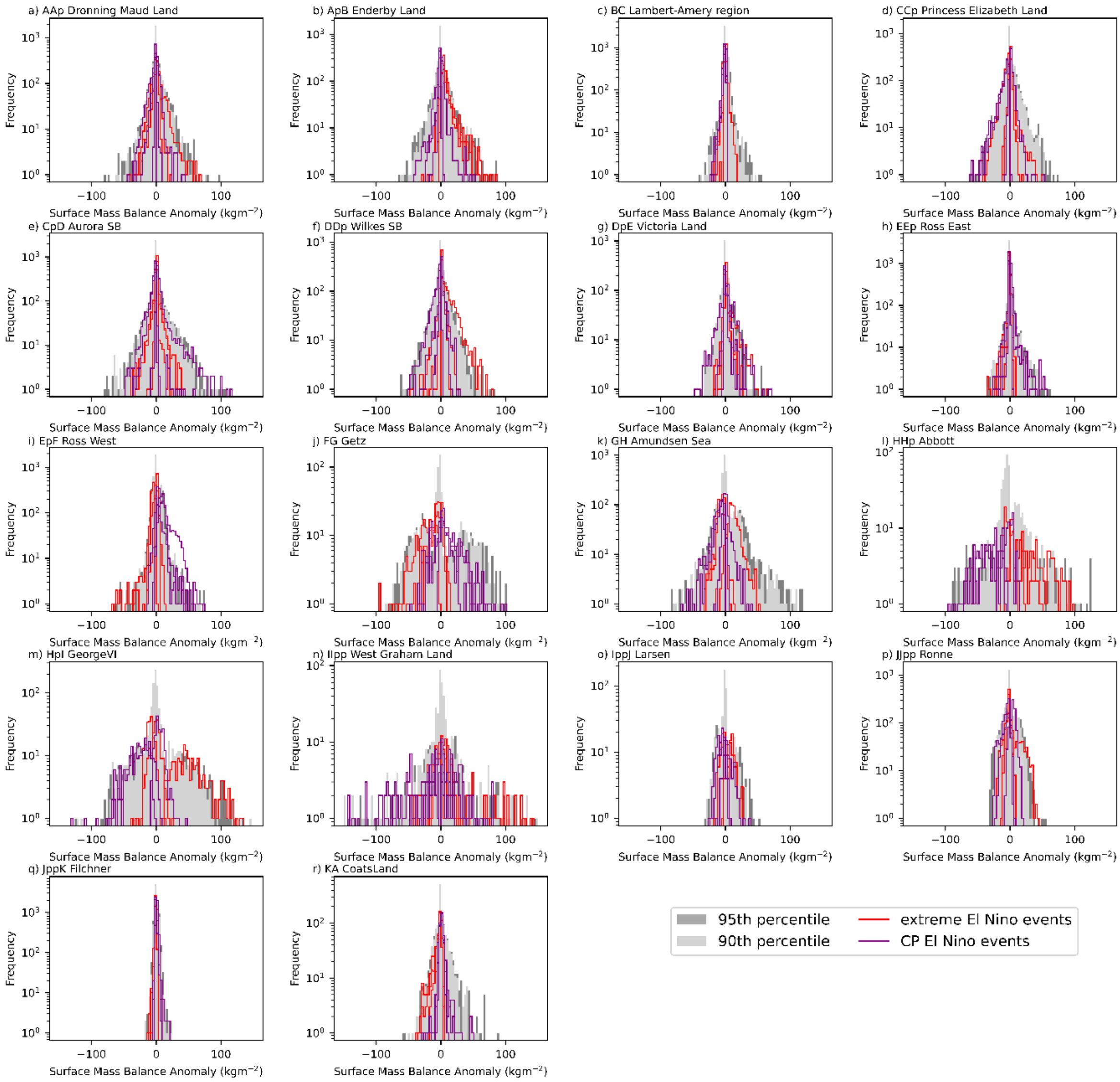


**Figure S9. Probability distributions of regional Antarctic surface mass balance anomalies during extreme El Niño events and CP El Niño events in SON.** Regional SMB probability distributions of SMB changes in SON for extreme El Niño events (red lines) and CP events (purple lines), and regional 90th (light grey shading) and 95th percentile (dark grey shading) SMB anomalies for SON for 1979-2018 period.

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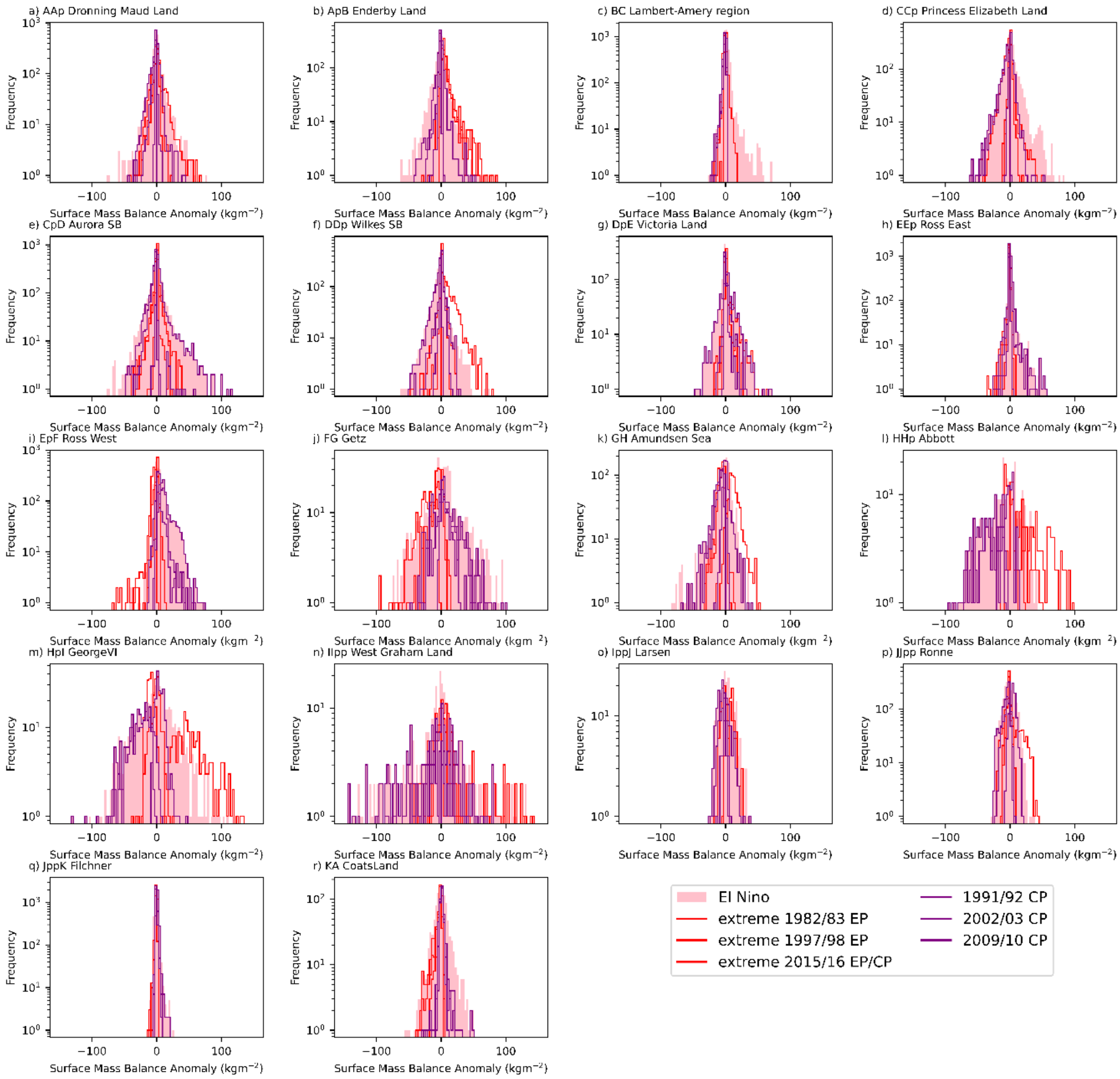


253 **Figure S10.** Regional SMB probability distributions of SMB changes in SON for El Niño
254 events excluding extreme events (pink shading), during extreme El Niño events (red lines)
255 and CP events (purple lines)

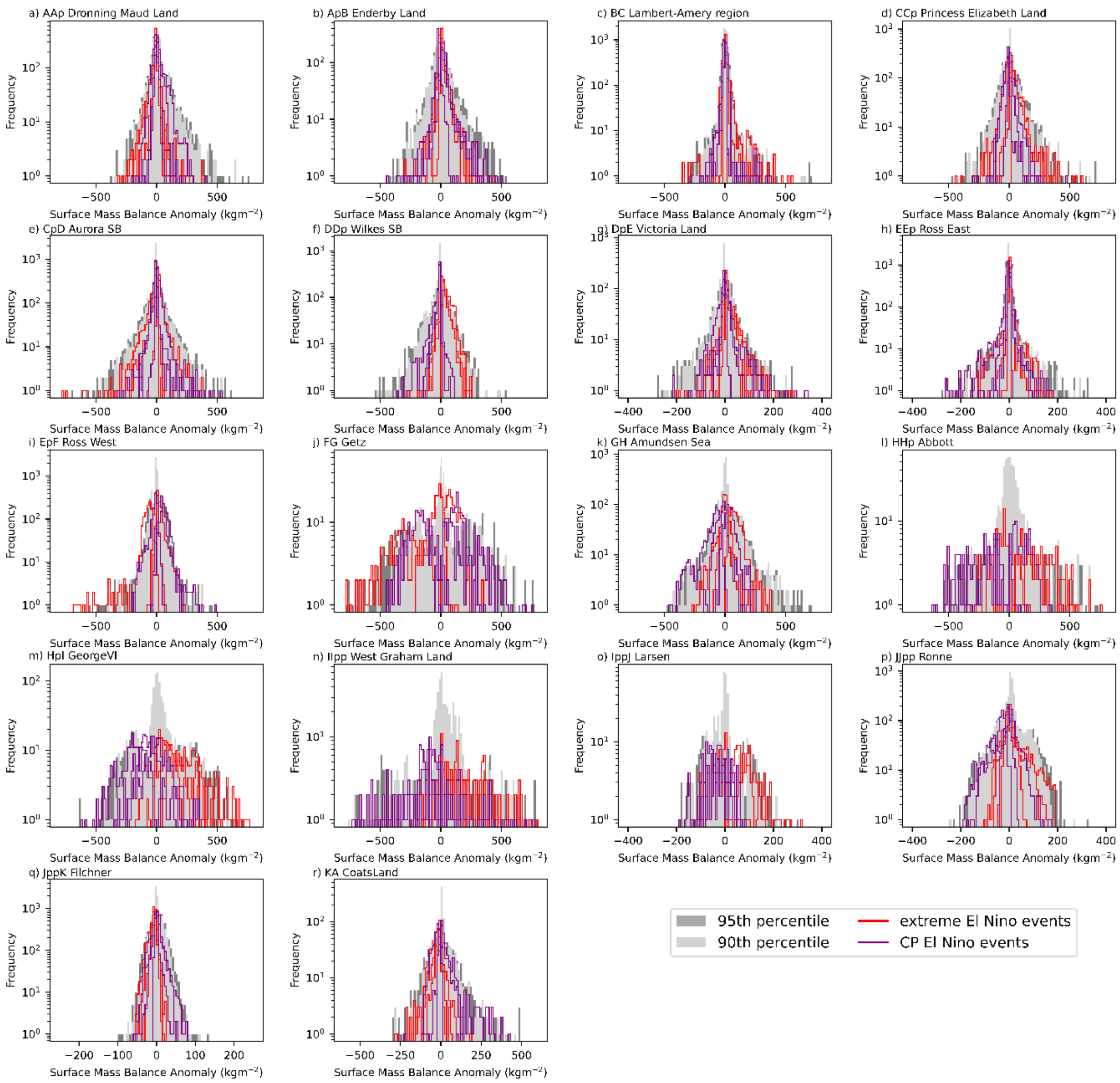


**Figure S11.** Regional SMB probability distributions of cumulative annual SMB anomalies (relative to 1979-2018 average) for extreme El Niño events (red lines) and CP events (purple lines), and regional 90th (light grey shading) and 95th percentile (dark grey shading) SMB anomalies for 1979-2018 period.

**S8. Statistical significance testing of regional SMB anomalies distributions during extreme El Niño events.**

| | Kolmogorov-Smirnov (K-S) test | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 1982/83 | | 1997/98 | | 2015/16 | | 1991/92 | | 2002/03 | | 2009/10 | |
| | statistic | *p-value* | statistic | *p-value* | statistic | *p-value* | statistic | *p-value* | statistic | *p-value* | statistic | *p-value* |
| AAp | 0.330 | <0.001 | 0.187 | <0.001 | 0.152 | <0.001 | 0.546 | <0.001 | 0.467 | <0.001 | 0.308 | <0.001 |
| ApB | 0.539 | <0.001 | 0.680 | <0.001 | 0.562 | <0.001 | 0.250 | <0.001 | 0.511 | <0.001 | 0.261 | <0.001 |
| BC | 0.263 | <0.001 | 0.110 | <0.001 | 0.396 | <0.001 | 0.370 | <0.001 | 0.330 | <0.001 | 0.175 | <0.001 |
| CCp | 0.331 | <0.001 | 0.354 | <0.001 | 0.579 | <0.001 | 0.615 | <0.001 | 0.534 | <0.001 | 0.422 | <0.001 |
| CpD | 0.481 | <0.001 | 0.162 | <0.001 | 0.087 | <0.001 | 0.569 | <0.001 | 0.574 | <0.001 | 0.521 | <0.001 |
| DDp | 0.452 | <0.001 | 0.281 | <0.001 | 0.628 | <0.001 | 0.336 | <0.001 | 0.186 | <0.001 | 0.540 | <0.001 |
| DpE | 0.492 | <0.001 | 0.184 | <0.001 | 0.258 | <0.001 | 0.141 | <0.001 | 0.531 | <0.001 | 0.251 | <0.001 |
| EEp | 0.201 | <0.001 | 0.465 | <0.001 | 0.371 | <0.001 | 0.155 | <0.001 | 0.201 | <0.001 | 0.488 | <0.001 |
| EpF | 0.104 | <0.001 | 0.651 | <0.001 | 0.367 | <0.001 | 0.680 | <0.001 | 0.744 | <0.001 | 0.447 | <0.001 |
| FG | 0.266 | <0.001 | 0.563 | <0.001 | 0.326 | <0.001 | 0.468 | <0.001 | 0.326 | <0.001 | 0.085 | 0.144 |
| GH | 0.393 | <0.001 | 0.347 | <0.001 | 0.638 | <0.001 | 0.326 | <0.001 | 0.509 | <0.001 | 0.376 | <0.001 |
| HHp | 0.303 | <0.001 | 0.490 | <0.001 | 0.753 | 0.241 | 0.264 | <0.001 | 0.609 | <0.001 | 0.543 | <0.001 |
| HpI | 0.422 | <0.001 | 0.231 | <0.001 | 0.751 | <0.001 | 0.390 | <0.001 | 0.485 | <0.001 | 0.611 | <0.001 |
| IIpp | 0.221 | 0.002 | 0.172 | 0.005 | 0.356 | <0.001 | 0.164 | 0.014 | 0.402 | <0.001 | 0.184 | 0.002 |
| IppJ | 0.239 | <0.001 | 0.408 | <0.001 | 0.512 | <0.001 | 0.342 | <0.001 | 0.408 | <0.001 | 0.316 | <0.001 |
| JJpp | 0.361 | <0.001 | 0.259 | <0.001 | 0.220 | <0.001 | 0.450 | <0.001 | 0.403 | <0.001 | 0.402 | <0.001 |
| JppK | 0.209 | <0.001 | 0.469 | <0.001 | 0.450 | <0.001 | 0.395 | <0.001 | 0.203 | <0.001 | 0.329 | <0.001 |
| K | 0.369 | <0.001 | 0.312 | <0.001 | 0.288 | <0.001 | 0.292 | <0.001 | 0.163 | 0.208 | 0.378 | <0.001 |

**Table S1.** Kolmogorov-Smirnov test statistics and *p-value* results showing statistically significant difference in SMB SON distributions for extreme El Niño events (1982/83, 1997/98, 2015/16) and CP El Niño events (1991/92, 2002/03, 2009/10) for each Antarctic region compared to the SMB SON distribution for the region for the full 1979-2018 time period with Monte-Carlo Sampling and 1000 simulations. Results in **bold** are statistically significant at the 5% significance level.

| | | Kolmogorov-Smirnov (K-S) test | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 1997/98 | | 2015/16 | | 1991/92 | | 2002/03 | | 2009/10 | |
| | | statistic | *p-value* | statistic | *p-value* | statistic | *p-value* | statistic | *p-value* | statistic | *p-value* |
| AAp | 1982/83 | **0.4212** | **<0.001** | **0.25597** | **<0.001** | **0.75072** | **<0.001** | **0.68577** | **<0.001** | **0.20248** | **<0.001** |
| | 1997/98 | 0.000 | 1.000 | **0.33047** | **<0.001** | **0.38109** | **<0.001** | **0.3171** | **<0.001** | **0.47851** | **<0.001** |
| | 2015/16 | | | 0.000 | 1.000 | **0.69628** | **<0.001** | **0.61032** | **<0.001** | **0.16523** | **<0.001** |
| | 1991/92 | | | | | 0.000 | 1.000 | **0.30946** | **<0.001** | **0.85005** | **<0.001** |
| | 2002/03 | | | | | | | 0.000 | 1.000 | **0.76504** | **<0.001** |
| ApB | 1982/83 | **0.20629** | **<0.001** | **0.14219** | **<0.001** | **0.75758** | **<0.001** | **0.89977** | **<0.001** | **0.50583** | **<0.001** |
| | 1997/98 | 0.000 | 1.000 | **0.12238** | **<0.001** | **0.92424** | **<0.001** | **0.98718** | **<0.001** | **0.669** | **<0.001** |
| | 2015/16 | | | 0.000 | 1.000 | **0.80769** | **<0.001** | **0.89277** | **<0.001** | **0.55245** | **<0.001** |
| | 1991/92 | | | | | 0.000 | 1.000 | **0.59557** | **<0.001** | **0.26923** | **<0.001** |
| | 2002/03 | | | | | | | 0.000 | 1.000 | **0.77156** | **<0.001** |
| BC | 1982/83 | **0.33525** | **<0.001** | **0.60046** | **<0.001** | **0.6194** | **<0.001** | **0.58611** | **<0.001** | **0.17394** | **<0.001** |
| | 1997/98 | 0.000 | 1.000 | **0.45867** | **<0.001** | **0.38576** | **<0.001** | **0.2744** | **<0.001** | **0.26693** | **<0.001** |
| | 2015/16 | | | 0.000 | 1.000 | **0.09357** | **<0.001** | **0.27669** | **<0.001** | **0.54363** | **<0.001** |
| | 1991/92 | | | | | 0.000 | 1.000 | **0.19805** | **<0.001** | **0.52928** | **<0.001** |
| | 2002/03 | | | | | | | 0.000 | 1.000 | **0.50459** | **<0.001** |
| CCp | 1982/83 | **0.16945** | **<0.001** | **0.89075** | **<0.001** | **0.90301** | **<0.001** | **0.85842** | **<0.001** | **0.23523** | **<0.001** |
| | 1997/98 | 0.000 | 1.000 | **0.9175** | **0.016** | **0.92642** | **<0.001** | 0.88852 | 0.106 | **0.3311** | **<0.001** |
| | 2015/16 | | | 0.000 | 1.000 | **0.10814** | **<0.001** | **0.05128** | **<0.001** | **0.92419** | **<0.001** |
| | 1991/92 | | | | | 0.000 | 1.000 | **0.12152** | **<0.001** | **0.93088** | **<0.001** |
| | 2002/03 | | | | | | | 0.000 | 1.000 | **0.90635** | **<0.001** |
| CpD | 1982/83 | **0.43324** | **<0.001** | **0.46996** | **<0.001** | **0.94726** | **<0.001** | **0.92857** | **<0.001** | **0.31976** | **<0.001** |
| | 1997/98 | 0.000 | 1.000 | **0.18158** | **<0.001** | **0.68892** | **<0.001** | **0.68892** | **<0.001** | **0.5988** | **<0.001** |
| | 2015/16 | | | 0.000 | 1.000 | **0.64486** | **<0.001** | **0.65421** | **<0.001** | **0.50868** | **<0.001** |
| | 1991/92 | | | | | 0.000 | 1.000 | **0.11081** | **<0.001** | **0.97597** | **<0.001** |
| | 2002/03 | | | | | | | 0.000 | 1.000 | **0.96061** | **<0.001** |
| DDp | 1982/83 | **0.20348** | **<0.001** | **0.64635** | **<0.001** | **0.31665** | **<0.001** | **0.44831** | **<0.001** | **0.90098** | **<0.001** |
| | 1997/98 | 0.000 | 1.000 | **0.54516** | **<0.001** | **0.16104** | **<0.001** | **0.28509** | **<0.001** | **0.76061** | **<0.001** |
| | 2015/16 | | | 0.000 | 1.000 | **0.66268** | **<0.001** | **0.57345** | **<0.001** | **0.98803** | **<0.001** |
| | 1991/92 | | | | | 0.000 | 1.000 | **0.24157** | **0.023** | **0.86289** | **<0.001** |
| | 2002/03 | | | | | | | 0.000 | 1.000 | **0.72035** | **<0.001** |
| DpE | 1982/83 | **0.37961** | **<0.001** | **0.32337** | **<0.001** | **0.52197** | **<0.001** | **0.4007** | **<0.001** | **0.72408** | **<0.001** |
| | 1997/98 | 0.000 | 1.000 | **0.2478** | **<0.001** | **0.2355** | **<0.001** | **0.52373** | **<0.001** | **0.41476** | **<0.001** |
| | 2015/16 | | | 0.000 | 1.000 | **0.27768** | **<0.001** | **0.32865** | **<0.001** | **0.46924** | **<0.001** |
| | 1991/92 | | | | | 0.000 | 1.000 | **0.48155** | **<0.001** | **0.33743** | **<0.001** |
| | 2002/03 | | | | | | | 0.000 | 1.000 | **0.69596** | **0.047** |
| EEp | 1982/83 | **0.34936** | **<0.001** | **0.22254** | **<0.001** | **0.28571** | **<0.001** | **0.27676** | **<0.001** | **0.4743** | **<0.001** |
| | 1997/98 | 0.000 | 1.000 | **0.25365** | **<0.001** | **0.48986** | **<0.001** | **0.43517** | **<0.001** | **0.21641** | **<0.001** |
| | 2015/16 | | | 0.000 | 1.000 | **0.43517** | **<0.001** | **0.36822** | **<0.001** | **0.34559** | **<0.001** |
| | 1991/92 | | | | | 0.000 | 1.000 | **0.17067** | **<0.001** | **0.54125** | **<0.001** |
| | 2002/03 | | | | | | | 0.000 | 1.000 | **0.46157** | **<0.001** |
| EpF | 1982/83 | **0.62098** | **<0.001** | **0.44986** | **<0.001** | **0.77921** | **<0.001** | **0.84085** | **<0.001** | **0.53818** | **<0.001** |
| | 1997/98 | 0.000 | 1.000 | **0.93008** | **<0.001** | **0.99264** | **<0.001** | **0.98896** | **<0.001** | **0.89052** | **<0.001** |
| | 2015/16 | | | 0.000 | 1.000 | 0.77921 | 0.107 | **0.86569** | **<0.001** | **0.45538** | **<0.001** |
| | 1991/92 | | | | | 0.000 | 1.000 | **0.29255** | **<0.001** | **0.49402** | **<0.001** |
| | 2002/03 | | | | | | | 0.000 | 1.000 | **0.62466** | **<0.001** |

**Table S2.** *(continued on next page)* Kolmogorov-Smirnov test statistics and *p-value* results showing statistically significant difference between SMB SON distributions between each extreme El Niño event (1982/83, 1997/98, 2015/16) and each CP El Niño event (1991/92, 2002/03, 2009/10) for each Antarctic region, with Monte-Carlo Sampling and 1000 simulations. Results in **bold** are statistically significant at the 5% significance level.

| | | Kolmogorov-Smirnov (K-S) test | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 1997/98 | | 2015/16 | | 1991/92 | | 2002/03 | | 2009/10 | |
| | | statistic | *p-value* | statistic | *p-value* | statistic | *p-value* | statistic | *p-value* | statistic | *p-value* |
| FG | 1982/83 | **0.625** | **<0.001** | **0.21591** | **<0.001** | 0.65909 | **<0.001** | **0.54545** | **<0.001** | **0.26136** | **<0.001** |
| | 1997/98 | 0.000 | 1.000 | **0.44318** | **<0.001** | 0.98864 | **<0.001** | **0.8125** | **<0.001** | **0.56818** | **<0.001** |
| | 2015/16 | | | 0.000 | 1.000 | 0.73864 | **<0.001** | **0.61932** | **<0.001** | **0.35227** | **<0.001** |
| | 1991/92 | | | | | 0.000 | 1.000 | **0.1875** | **<0.001** | **0.4375** | **<0.001** |
| | 2002/03 | | | | | | | 0.000 | 1.000 | **0.30114** | **<0.001** |
| GH | 1982/83 | **0.22442** | **<0.001** | **0.90305** | **<0.001** | **0.68402** | **<0.001** | **0.2316** | **<0.001** | **0.1526** | **<0.001** |
| | 1997/98 | 0.000 | 1.000 | **0.92819** | **<0.001** | **0.59246** | **<0.001** | **0.37702** | **<0.001** | **0.19569** | **<0.001** |
| | 2015/16 | | | 0.000 | 1.000 | **0.7289** | **<0.001** | **0.96409** | **<0.001** | **0.92998** | **<0.001** |
| | 1991/92 | | | | | 0.000 | 1.000 | **0.81329** | **<0.001** | **0.63375** | **<0.001** |
| | 2002/03 | | | | | | | 0.000 | 1.000 | **0.21903** | **<0.001** |
| HHp | 1982/83 | **0.59524** | **<0.001** | 0.95238 | 0.064 | **0.14286** | **<0.001** | 0.89286 | **<0.001** | **0.79762** | **<0.001** |
| | 1997/98 | 0.000 | 1.000 | **0.63095** | **<0.001** | **0.52381** | **<0.001** | 0.9881 | **<0.001** | **0.97619** | **<0.001** |
| | 2015/16 | | | 0.000 | 1.000 | **0.878** | 0.281 | 0.810 | **<0.001** | 0.91526 | 0.084 |
| | 1991/92 | | | | | 0.000 | 1.000 | 0.83333 | 0.362 | **0.71429** | **<0.001** |
| | 2002/03 | | | | | | | 0.000 | 1.000 | 0.15476 | 0.072 |
| Hpl | 1982/83 | **0.52941** | **<0.001** | **0.9893** | **<0.001** | **0.78075** | **<0.001** | **0.51872** | **<0.001** | **0.68984** | **<0.001** |
| | 1997/98 | 0.000 | 1.000 | **0.96257** | **<0.001** | **0.37968** | **<0.001** | **0.65241** | **<0.001** | **0.80214** | **<0.001** |
| | 2015/16 | | | 0.000 | 1.000 | **0.89305** | **<0.001** | 0.784 | 0.069 | 0.617 | 0.181 |
| | 1991/92 | | | | | 0.000 | 1.000 | **0.86096** | **<0.001** | **0.97326** | **<0.001** |
| | 2002/03 | | | | | | | 0.000 | 1.000 | **0.20321** | **<0.001** |
| IIpp | 1982/83 | **0.21875** | **<0.001** | **0.34375** | **<0.001** | **0.16667** | **<0.001** | **0.59375** | **<0.001** | **0.38542** | **<0.001** |
| | 1997/98 | 0.000 | 1.000 | **0.48958** | **<0.001** | **0.21875** | **<0.001** | **0.45833** | **<0.001** | **0.26042** | **<0.001** |
| | 2015/16 | | | 0.000 | 1.000 | **0.38542** | **<0.001** | **0.64583** | **<0.001** | **0.41667** | **<0.001** |
| | 1991/92 | | | | | 0.000 | 1.000 | **0.55208** | **<0.001** | **0.33333** | **<0.001** |
| | 2002/03 | | | | | | | 0.000 | 1.000 | **0.35417** | **<0.001** |
| IppJ | 1982/83 | **0.5679** | **<0.001** | 0.71605 | 0.011 | **0.22222** | **<0.001** | **0.48148** | **<0.001** | **0.4321** | **<0.001** |
| | 1997/98 | 0.000 | 1.000 | **0.22222** | **<0.001** | 0.7037 | 0.252 | **0.80247** | **<0.001** | **0.20988** | **<0.001** |
| | 2015/16 | | | 0.000 | 1.000 | **0.83951** | **<0.001** | **0.83951** | **<0.001** | **0.39506** | **<0.001** |
| | 1991/92 | | | | | 0.000 | 1.000 | **0.34568** | **<0.001** | **0.60494** | **<0.001** |
| | 2002/03 | | | | | | | 0.000 | 1.000 | **0.7037** | **<0.001** |
| JJpp | 1982/83 | 0.2503 | **<0.001** | **0.44164** | **<0.001** | **0.77617** | **<0.001** | **0.35981** | **<0.001** | **0.14801** | **<0.001** |
| | 1997/98 | 0.000 | 1.000 | **0.38628** | **<0.001** | **0.68592** | **<0.001** | **0.55836** | **<0.001** | **0.38267** | **<0.001** |
| | 2015/16 | | | 0.000 | 1.000 | **0.35018** | **<0.001** | **0.44525** | **<0.001** | **0.47774** | **<0.001** |
| | 1991/92 | | | | | 0.000 | 1.000 | **0.75572** | **<0.001** | **0.80987** | **<0.001** |
| | 2002/03 | | | | | | | 0.000 | 1.000 | **0.29723** | **<0.001** |
| JppK | 1982/83 | **0.47135** | **<0.001** | **0.4627** | **<0.001** | **0.41477** | **<0.001** | **0.2** | **<0.001** | **0.32937** | **<0.001** |
| | 1997/98 | 0.000 | 1.000 | **0.1236** | **<0.001** | **0.84108** | **<0.001** | **0.36685** | **<0.001** | **0.52865** | **<0.001** |
| | 2015/16 | | | 0.000 | 1.000 | **0.83748** | **<0.001** | **0.29441** | **<0.001** | **0.47568** | **<0.001** |
| | 1991/92 | | | | | 0.000 | 1.000 | **0.58919** | **<0.001** | **0.72288** | **<0.001** |
| | 2002/03 | | | | | | | 0.000 | 1.000 | **0.18883** | **<0.001** |
| K | 1982/83 | **0.35613** | **<0.001** | **0.1396** | **<0.001** | **0.65527** | **<0.001** | **0.50427** | **<0.001** | **0.70085** | **<0.001** |
| | 1997/98 | 0.000 | 1.000 | **0.32479** | **<0.001** | 0.34473 | 0.106 | **0.39886** | **<0.001** | **0.48718** | **<0.001** |
| | 2015/16 | | | 0.000 | 1.000 | **0.54416** | **<0.001** | **0.4188** | **<0.001** | **0.63533** | **<0.001** |
| | 1991/92 | | | | | 0.000 | 1.000 | **0.1567** | **<0.001** | **0.19658** | **<0.001** |
| | 2002/03 | | | | | | | 0.000 | 1.000 | **0.22792** | **<0.001** |

## S9. Regional SMB histograms during strong La Niña events

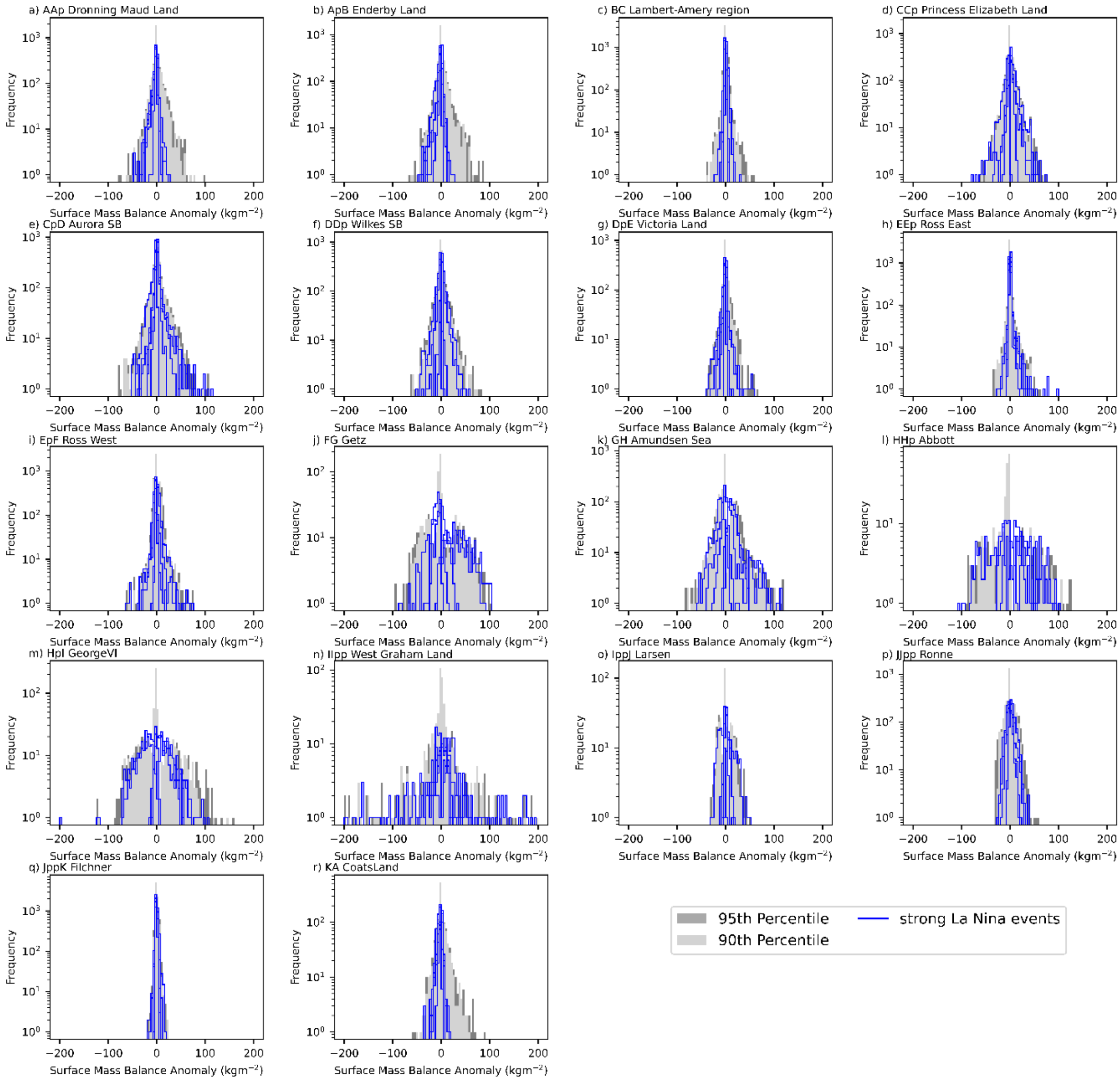


**Figure S12.** Regional SMB probability distributions of SMB changes in SON for strong La Niña events (blue lines), and regional 90th (light grey shading) and 95th percentile (dark grey shading) SMB anomalies for SON for 1979-2018 period.

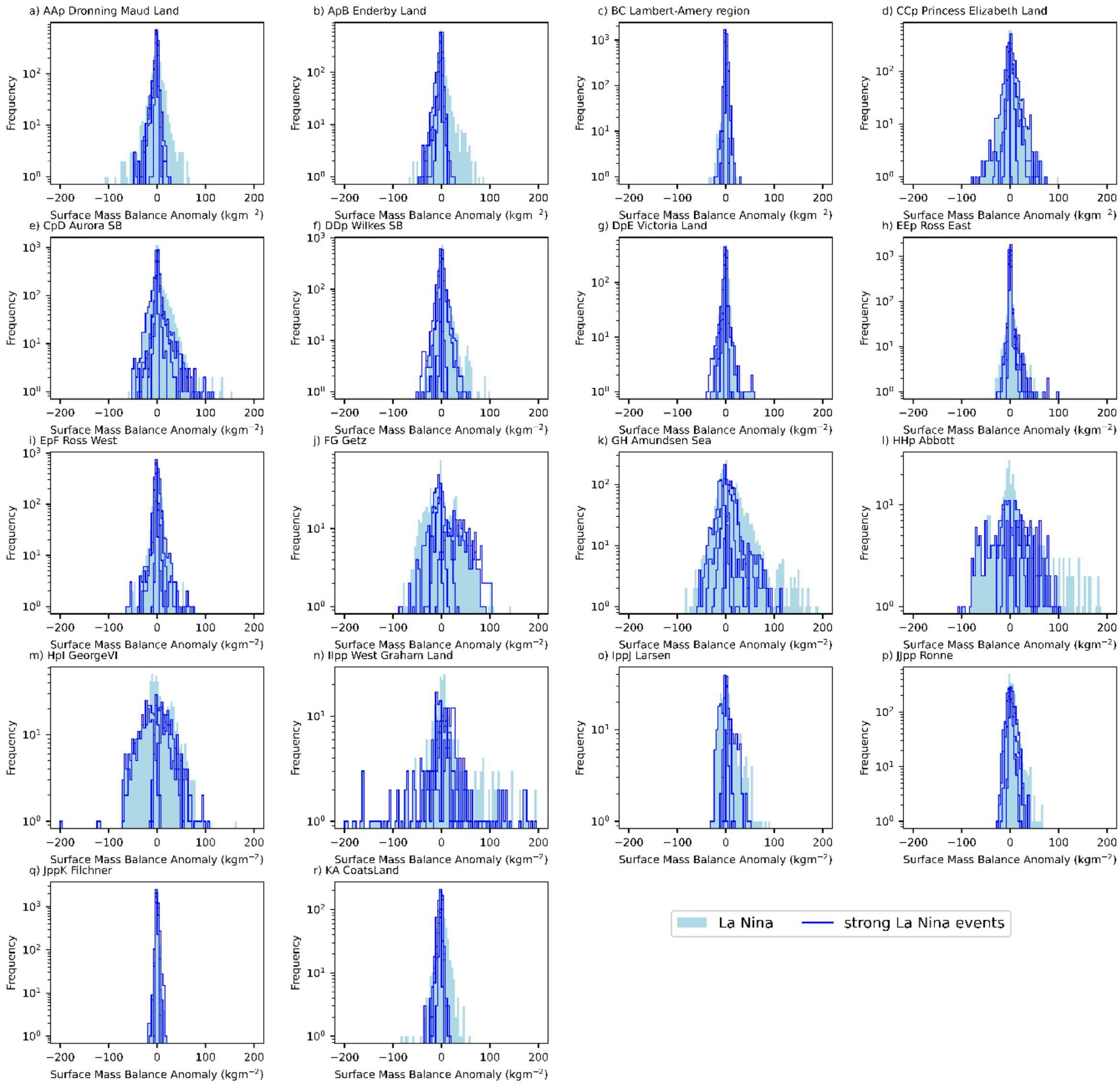


**Figure S13.** Regional SMB probability distributions of SMB changes in SON for La Niña events excluding strong events (light blue shading), during strong La Niña events (blue lines).

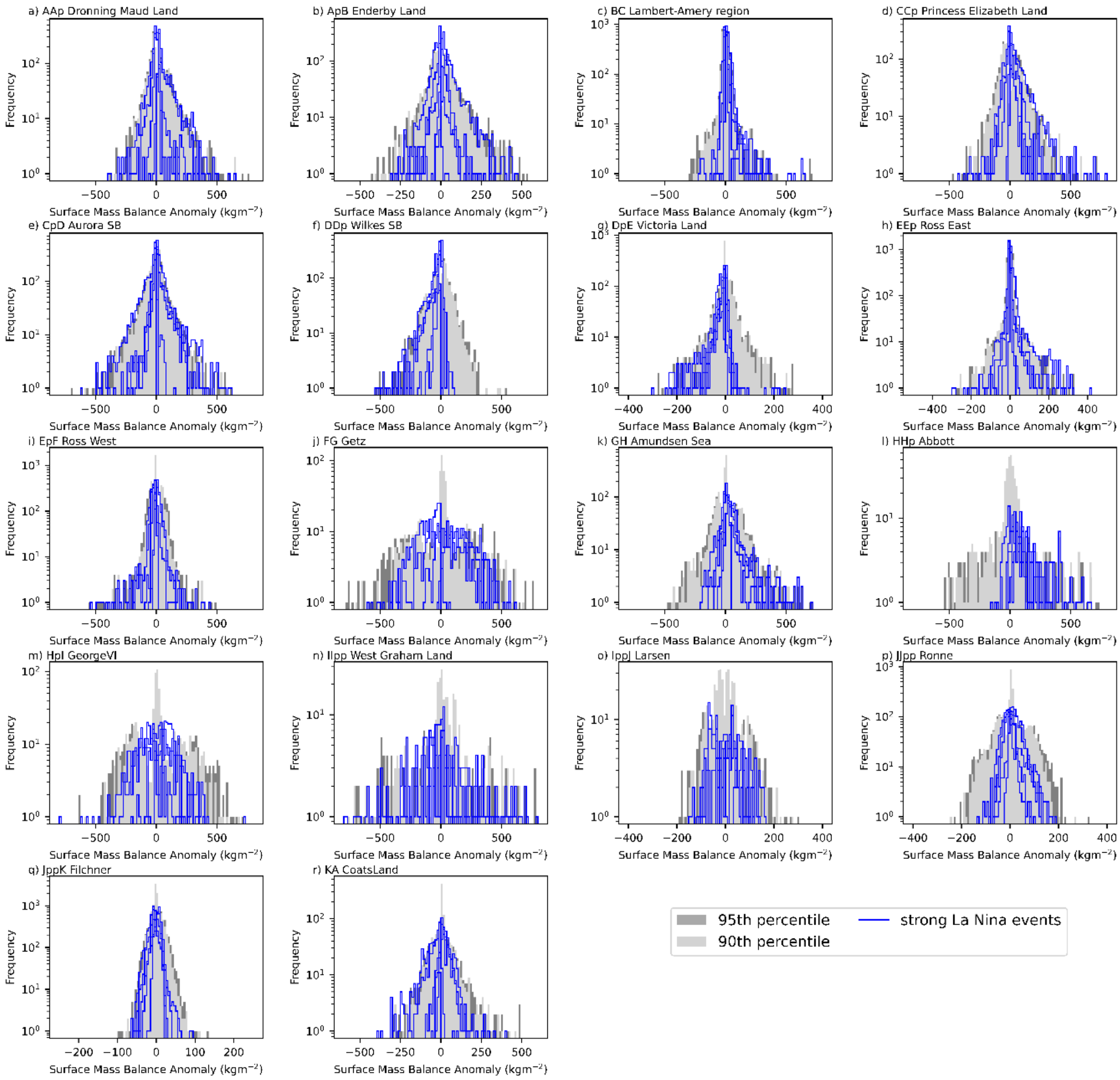


**Figure S14.** Regional SMB probability distributions of cumulative annual SMB anomalies (relative to 1979-2018 average) for strong La Niña events (blue lines) and regional 90th (light grey shading) and 95th percentile (dark grey shading) SMB anomalies for 1979-2018 period.

**S10. Statistical significance testing of regional SMB anomalies distributions during strong La Niña events.**

| | Kolmogorov-Smirnov (K-S) test | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | 1988/89 | | 1998/99 | | 1999/00 | | 2007/08 | | 2010/11 | |
| | statistic | p-value | statistic | p-value | statistic | p-value | statistic | p-value | statistic | p-value |
| AAp | **0.266** | **<0.001** | **0.231** | **<0.001** | **0.181** | **<0.001** | **0.227** | **<0.001** | **0.257** | **<0.001** |
| ApB | **0.413** | **<0.001** | **0.233** | **<0.001** | **0.629** | **<0.001** | **0.495** | **<0.001** | **0.531** | **<0.001** |
| BC | **0.218** | **<0.001** | **0.320** | **<0.001** | **0.390** | **<0.001** | **0.226** | **<0.001** | **0.598** | **<0.001** |
| CCp | **0.527** | **<0.001** | **0.208** | **<0.001** | **0.544** | **<0.001** | **0.300** | **<0.001** | **0.346** | **<0.001** |
| CpD | **0.236** | **<0.001** | **0.290** | **<0.001** | **0.563** | **<0.001** | **0.292** | **<0.001** | **0.208** | **<0.001** |
| DDp | **0.409** | **<0.001** | **0.485** | **<0.001** | **0.352** | **<0.001** | **0.538** | **<0.001** | **0.176** | **<0.001** |
| DpE | **0.566** | **<0.001** | **0.511** | **<0.001** | **0.388** | **<0.001** | **0.172** | **<0.001** | **0.498** | **<0.001** |
| EEp | **0.434** | **<0.001** | **0.505** | **<0.001** | **0.454** | **<0.001** | **0.276** | **<0.001** | **0.171** | **<0.001** |
| EpF | **0.364** | **<0.001** | **0.346** | **<0.001** | **0.221** | **<0.001** | **0.399** | **<0.001** | **0.203** | **<0.001** |
| FG | **0.342** | **<0.001** | **0.625** | **<0.001** | **0.234** | **<0.001** | **0.601** | **<0.001** | **0.510** | **<0.001** |
| GH | **0.368** | **<0.001** | **0.767** | **<0.001** | 0.056 | 0.085 | **0.580** | **<0.001** | **0.101** | **<0.001** |
| HHp | **0.508** | **<0.001** | **0.714** | **<0.001** | **0.212** | **<0.001** | **0.552** | **<0.001** | **0.281** | **<0.001** |
| HpI | **0.404** | **<0.001** | **0.595** | **<0.001** | **0.624** | **<0.001** | **0.224** | **<0.001** | **0.482** | **<0.001** |
| IIpp | **0.478** | **<0.001** | **0.272** | **<0.001** | **0.192** | **<0.001** | **0.484** | **<0.001** | **0.411** | **<0.001** |
| IppJ | **0.341** | **<0.001** | **0.478** | **<0.001** | **0.449** | **<0.001** | **0.749** | **<0.001** | **0.651** | **<0.001** |
| JJpp | **0.200** | **<0.001** | **0.535** | **<0.001** | **0.314** | **<0.001** | **0.191** | **<0.001** | **0.643** | **<0.001** |
| JppK | **0.423** | **<0.001** | **0.042** | **<0.001** | **0.174** | **<0.001** | **0.280** | **<0.001** | **0.454** | **<0.001** |
| K | **0.176** | **<0.001** | **0.209** | **<0.001** | **0.360** | **<0.001** | **0.197** | **<0.001** | **0.313** | **<0.001** |

**Table S3.** Kolmogorov-Smirnov test statistics and *p-value* results showing statistically significant difference in SMB SON distributions for strong La Niña events (1988/89, 1998/99, 1999/00, 2007/08, 2010/11) for each Antarctic region compared to the SMB SON distribution for the region for the full 1979-2018 time period with Monte Carlo Sampling and 1000 simulations. Results in **bold** are statistically significant at the 5% significance level.

| | | Kolmogorov-Smirnov (K-S) test | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | 1998/99 | | 1999/00 | | 2007/08 | | 2010/11 | |
| | | statistic | *p-value* | statistic | *p-value* | statistic | *p-value* | statistic | *p-value* |
| AAp | 1988/89 | **0.191** | **<0.001** | **0.233** | **<0.001** | **0.238** | **<0.001** | **0.320** | **<0.001** |
| | 1998/99 | 0.000 | 1.000 | **0.388** | **<0.001** | **0.245** | **<0.001** | **0.452** | **<0.001** |
| | 1999/00 | | | 0.000 | 1.000 | **0.195** | **<0.001** | **0.166** | **<0.001** |
| | 2007/08 | | | | | 0.000 | 1.000 | **0.288** | **<0.001** |
| ApB | 1988/89 | **0.645** | **<0.001** | **0.900** | **<0.001** | **0.893** | **<0.001** | **0.473** | **<0.001** |
| | 1998/99 | 0.000 | 1.000 | 0.593 | <0.001 | **0.347** | **<0.001** | **0.728** | **<0.001** |
| | 1999/00 | | | 0.000 | 1.000 | **0.477** | **<0.001** | **0.928** | **<0.001** |
| | 2007/08 | | | | | 0.000 | 1.000 | **0.960** | **<0.001** |
| BC | 1988/89 | **0.528** | **<0.001** | **0.334** | **<0.001** | **0.108** | **<0.001** | **0.797** | **<0.001** |
| | 1998/99 | 0.000 | 1.000 | 0.661 | 0.103 | **0.525** | **<0.001** | **0.389** | **<0.001** |
| | 1999/00 | | | 0.000 | 1.000 | **0.286** | **<0.001** | **0.883** | **<0.001** |
| | 2007/08 | | | | | 0.000 | 1.000 | **0.823** | **<0.001** |
| CCp | 1988/89 | **0.727** | **<0.001** | **0.182** | **<0.001** | **0.713** | **<0.001** | **0.870** | **<0.001** |
| | 1998/99 | 0.000 | 1.000 | **0.749** | **<0.001** | **0.236** | **<0.001** | **0.202** | **<0.001** |
| | 1999/00 | | | 0.000 | 1.000 | **0.829** | **<0.001** | **0.880** | **<0.001** |
| | 2007/08 | | | | | 0.000 | 1.000 | **0.219** | **<0.001** |
| CpD | 1988/89 | **0.404** | **<0.001** | **0.633** | **<0.001** | **0.328** | **<0.001** | **0.361** | **<0.001** |
| | 1998/99 | 0.000 | 1.000 | **0.812** | **<0.001** | **0.132** | **<0.001** | **0.175** | **<0.001** |
| | 1999/00 | | | 0.000 | 1.000 | **0.853** | **<0.001** | **0.700** | **<0.001** |
| | 2007/08 | | | | | 0.000 | 1.000 | **0.163** | **<0.001** |
| DDp | 1988/89 | **0.868** | **<0.001** | **0.178** | **<0.001** | **0.923** | **<0.001** | **0.277** | **<0.001** |
| | 1998/99 | 0.000 | 1.000 | **0.834** | **<0.001** | **0.138** | **<0.001** | **0.603** | **<0.001** |
| | 1999/00 | | | 0.000 | 1.000 | **0.873** | **<0.001** | **0.245** | **<0.001** |
| | 2007/08 | | | | | 0.000 | 1.000 | **0.664** | **<0.001** |
| DpE | 1988/89 | **0.953** | **<0.001** | **0.821** | **<0.001** | **0.703** | **<0.001** | **0.445** | **<0.001** |
| | 1998/99 | 0.000 | 1.000 | **0.399** | **<0.001** | **0.678** | **<0.001** | **0.794** | **<0.001** |
| | 1999/00 | | | 0.000 | 1.000 | **0.548** | **<0.001** | **0.659** | **<0.001** |
| | 2007/08 | | | | | 0.000 | 1.000 | **0.617** | **<0.001** |
| EEp | 1988/89 | **0.289** | **<0.001** | **0.842** | **<0.001** | **0.700** | **<0.001** | **0.488** | **<0.001** |
| | 1998/99 | 0.000 | 1.000 | **0.854** | **<0.001** | **0.728** | **<0.001** | **0.488** | **<0.001** |
| | 1999/00 | | | 0.000 | 1.000 | **0.423** | **<0.001** | **0.388** | **<0.001** |
| | 2007/08 | | | | | 0.000 | 1.000 | **0.290** | **<0.001** |
| EpF | 1988/89 | **0.176** | **<0.001** | **0.329** | **<0.001** | **0.759** | **<0.001** | **0.555** | **<0.001** |
| | 1998/99 | 0.000 | 1.000 | **0.330** | **<0.001** | **0.696** | **<0.001** | **0.454** | **<0.001** |
| | 1999/00 | | | 0.000 | 1.000 | **0.568** | **<0.001** | **0.298** | **<0.001** |
| | 2007/08 | | | | | 0.000 | 1.000 | **0.419** | **<0.001** |

**Table S4.** *(continued on next page).* Kolmogorov-Smirnov test statistics and *p-value* results showing statistically significant difference between SMB SON distributions between each strong La Niña events (1988/89, 1998/99, 1999/00, 2007/08, 2010/11) for each Antarctic region, with Monte Carlo Sampling and 1000 simulations. Results in **bold** are statistically significant at the 5% significance level.

| | | Kolmogorov-Smirnov (K-S) test | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | 1998/99 | | 1999/00 | | 2007/08 | | 2010/11 | |
| | | statistic | *p-value* | statistic | *p-value* | statistic | *p-value* | statistic | *p-value* |
| FG | 1988/89 | **0.943** | **<0.001** | **0.494** | **<0.001** | **0.813** | **<0.001** | **0.841** | **<0.001** |
| | 1998/99 | 0.000 | 1.000 | **0.761** | **<0.001** | **0.972** | **<0.001** | **0.159** | **<0.001** |
| | 1999/00 | | | 0.000 | 1.000 | **0.778** | **<0.001** | **0.665** | **<0.001** |
| | 2007/08 | | | | | 0.000 | 1.000 | **0.949** | **<0.001** |
| GH | 1988/89 | **0.937** | **<0.001** | **0.339** | **<0.001** | **0.930** | **<0.001** | **0.355** | **<0.001** |
| | 1998/99 | 0.000 | 1.000 | **0.792** | **<0.001** | **0.820** | **<0.001** | **0.741** | **<0.001** |
| | 1999/00 | | | 0.000 | 1.000 | **0.594** | **<0.001** | **0.115** | **<0.001** |
| | 2007/08 | | | | | 0.000 | 1.000 | **0.600** | **<0.001** |
| HHp | 1988/89 | **0.798** | **<0.001** | **0.488** | **<0.001** | **0.964** | **<0.001** | **0.774** | **<0.001** |
| | 1998/99 | 0.000 | 1.000 | **0.917** | **<0.001** | **0.832** | **<0.001** | **0.940** | **<0.001** |
| | 1999/00 | | | 0.000 | 1.000 | **0.726** | **<0.001** | **0.369** | **<0.001** |
| | 2007/08 | | | | | 0.000 | 1.000 | **0.417** | **<0.001** |
| Hpl | 1988/89 | **0.556** | **<0.001** | **0.631** | **<0.001** | **0.299** | **<0.001** | **0.856** | **<0.001** |
| | 1998/99 | 0.000 | 1.000 | **0.096** | **<0.001** | **0.679** | **<0.001** | **0.963** | **<0.001** |
| | 1999/00 | | | 0.000 | 1.000 | **0.733** | **<0.001** | **0.947** | **<0.001** |
| | 2007/08 | | | | | 0.000 | 1.000 | **0.695** | **<0.001** |
| IIpp | 1988/89 | **0.323** | **<0.001** | **0.583** | **<0.001** | **0.271** | **<0.001** | **0.792** | **<0.001** |
| | 1998/99 | 0.000 | 1.000 | 0.333 | 0.061 | 0.323 | 0.052 | 0.594 | 0.084 |
| | 1999/00 | | | 0.000 | 1.000 | **0.583** | **<0.001** | **0.344** | **<0.001** |
| | 2007/08 | | | | | 0.000 | 1.000 | **0.781** | **<0.001** |
| IppJ | 1988/89 | **0.778** | **<0.001** | 0.741 | 0.709 | **0.988** | **<0.001** | **0.951** | **<0.001** |
| | 1998/99 | 0.000 | 1.000 | **0.074** | **<0.001** | 0.975 | 0.744 | **0.296** | **<0.001** |
| | 1999/00 | | | 0.000 | 1.000 | **0.951** | **<0.001** | **0.346** | **<0.001** |
| | 2007/08 | | | | | 0.000 | 1.000 | **0.988** | **<0.001** |
| JJpp | 1988/89 | **0.685** | **<0.001** | **0.502** | **<0.001** | **0.153** | **<0.001** | **0.838** | **<0.001** |
| | 1998/99 | 0.000 | 1.000 | **0.750** | **<0.001** | **0.579** | **<0.001** | **0.929** | **<0.001** |
| | 1999/00 | | | 0.000 | 1.000 | **0.454** | **<0.001** | **0.721** | **<0.001** |
| | 2007/08 | | | | | 0.000 | 1.000 | **0.833** | **<0.001** |
| JppK | 1988/89 | **0.397** | **<0.001** | **0.591** | **<0.001** | **0.685** | **<0.001** | **0.178** | **<0.001** |
| | 1998/99 | 0.000 | 1.000 | **0.199** | **<0.001** | **0.304** | **<0.001** | **0.434** | **<0.001** |
| | 1999/00 | | | 0.000 | 1.000 | **0.140** | **<0.001** | **0.595** | **<0.001** |
| | 2007/08 | | | | | 0.000 | 1.000 | **0.721** | **<0.001** |
| K | 1988/89 | **0.228** | **<0.001** | **0.513** | **<0.001** | **0.356** | **<0.001** | **0.185** | **<0.001** |
| | 1998/99 | 0.000 | 1.000 | **0.379** | **<0.001** | 0.236 | 0.106 | **0.379** | **<0.001** |
| | 1999/00 | | | 0.000 | 1.000 | **0.202** | **<0.001** | **0.598** | **<0.001** |
| | 2007/08 | | | | | 0.000 | 1.000 | **0.459** | **<0.001** |

**S11. Violin plots of regional surface mass balance anomalies for moderate and strong El Niño events**

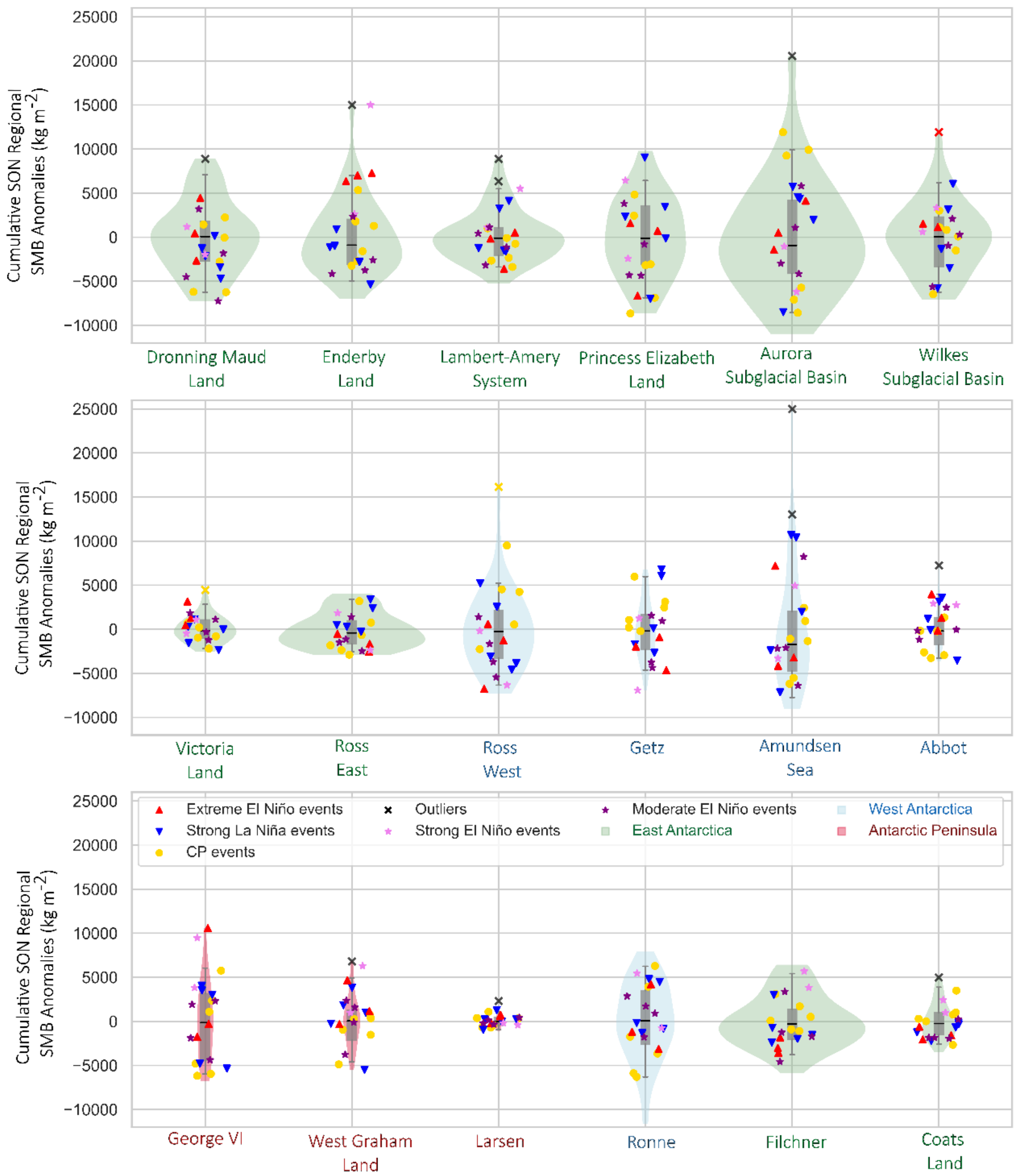


**Figure S15. Relationship between ENSO events and regional Antarctic surface mass balance anomalies during SON.** Density curves of regional cumulative SON SMB anomalies for each Antarctic Ice Sheet regional catchment, scaled by the regional catchment size. Box plots show the interquartile range (IQR), with medians (black line) and whiskers (5th and 95th percentiles). East Antarctic (light green), West Antarctic (light blue) and Antarctic Peninsula (pink) catchments, outliers (crosses; see supplement), extreme El Niño events (red), strong La Niña events (blue), Central Pacific El Niño events (yellow), strong El Niño events (pink) and moderate El Niño events (purple) are highlighted.

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