

The changing mass of the Antarctic Ice Sheet during ENSO-dominated periods in the GRACE era (2002–2022)

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Abstract. Large-scale modes of climate variability significantly influence Antarctic Ice Sheet (AIS) mass change. Improved understanding of the relationship between these climate modes and AIS mass change can help reduce uncertainties in future ice mass estimates and its contribution to sea level rise. However, the spatiotemporal patterns of AIS mass variation driven by El Niño Southern Oscillation (ENSO)-induced atmospheric circulation remain unclear. We investigated AIS mass variability during different ENSO periods using Gravity Recovery and Climate Experiment (GRACE) observed mass changes and modelled surface mass balance (using RACMO2.4p1) over the period 2002 to 2022. To allow comparison with GRACE, we used a cumulative sum indexing method to define different ENSO-dominated ‘periods’ over 2002–2022. This method results in time periods that are dominated by a particular phase of ENSO, that is not necessarily equivalent to specific events as derived from canonical indices. The results show strong spatial variability in how the ENSO teleconnection cumulatively manifests over the AIS. These differing spatial patterns are primarily driven by changes in the Amundsen Sea Low strength, location, and extent, which alter circulation patterns and moisture flow in West Antarctica. In East Antarctica, ice mass variability is largely influenced by the positioning of cyclonic and anticyclonic circulation anomalies, primarily driven by the Southern Annular Mode; however, ENSO signals are also present. In both East and West Antarctica, this study shows that the spatial impact of any given ENSO-dominant period can trigger distinct circulation patterns which can variably influence surface mass balance and ice mass change. However, uncertainties remain, as the mass variability observed during ENSO-dominant periods may not be solely attributed to ENSO, due to teleconnections that may not have fully developed or may have been masked by other processes.

1. Introduction

The drivers of inter-annual to decadal Antarctic Ice Sheet (AIS) mass variability are complex and not yet fully understood (IMBIE Team, 2018). External factors, such as episodic extreme precipitation events often linked to atmospheric rivers (Wille et al., 2021), and internal factors, including ice dynamics (IMBIE Team, 2018), both contribute to these variations. Understanding the mechanisms underlying AIS mass change and variability is critical for improving future projections of ice mass changes and the Antarctic contribution to sea level rise.

The main determinants of the net AIS mass balance (MB) are ice discharge (D) from the continental margins of Antarctica and Surface Mass Balance (SMB). SMB is further defined as accumulating precipitation and riming

39 onto the ice sheet, minus runoff, sublimation/evaporation and blowing snow erosion. The fluctuation of the AIS
40 mass balance and its subsequent contribution to sea level rise are based on the difference between ice discharge
41 and SMB (i.e., $MB = SMB - D$). The AIS SMB exhibits high variability on inter-annual to decadal timescales,
42 (Kim et al., 2020; Medley and Thomas, 2019; Van De Berg et al., 2006). Precipitation variability, driven by
43 atmospheric circulation, is a key determinant of Antarctic SMB and, over a wide range of timescales, including
44 interannual to decadal, is closely linked to modes of climate variability (Kim et al., 2020).

45 The Southern Annular Mode (SAM) is the dominant mode of extratropical variability in the Southern Hemisphere.
46 The SAM signal is driven by a combination of internal atmospheric dynamics and external forcings, including
47 stratospheric ozone depletion, increases in greenhouse gases, and tropical teleconnections (Fogt and Marshall,
48 2020a). It varies on timescales from weeks to decades, and its influence on Antarctic precipitation is regionally
49 dependent (Marshall et al., 2017). During the positive phase of SAM, the westerlies around 60° S strengthen, and
50 the overall impact on the AIS is a net decrease in SMB (Marshall et al., 2017; Medley and Thomas, 2019).
51 Conversely, the net influence of the negative phase of SAM on the AIS is an increase in SMB (Medley and
52 Thomas, 2019; Marshall et al., 2017). However, SAM related circulation patterns are not stationary and vary over
53 decades, meaning that the regional impacts may shift over time (Marshall et al., 2013).

54 The El Niño Southern Oscillation (ENSO) is the dominant mode of inter-annual climate variability globally (2–
55 7-year timescales) and is defined by variations in sea surface temperature (SST) anomalies in the tropical Pacific
56 (McPhaden et al., 2006). The ENSO pathway to Antarctica is modulated by the Amundsen Sea Low (ASL), which
57 lies at the poleward end of a Rossby wave train originating in the tropics (Hoskins and Karoly, 1981). This Rossby
58 wave train leads to the formation of the Pacific South American mode 1 (PSA-1), an atmospheric anomaly pattern
59 that enables ENSO signals to reach Antarctica (Hoskins and Karoly, 1981). This creates a positive pressure
60 anomaly over the Amundsen-Bellinghshausen sector (ABS) during El Niño events—the positive phase of PSA-1
61 and negative pressure anomaly during La Niña conditions—the negative phase of PSA-1 (Turner, 2004; Hoskins
62 and Karoly, 1981). The ASL represents a climatological area of low pressure in the South Pacific and is a key
63 component of the nonzonal climatological circulation (Raphael et al., 2016a). The teleconnection between ENSO
64 and the ASL is strongest during the austral spring (September–November; SON) but exerts influence throughout
65 the year (Schneider et al., 2012; Clem and Fogt, 2013; Fogt et al., 2011). The strength, extent, and location of the
66 ASL shows significant variability during different ENSO phases and individual ENSO events, resulting in varying
67 atmospheric circulation patterns that strongly influences moisture and temperature distribution in West Antarctica
68 (Raphael et al., 2016a; Hosking et al., 2013). The impact of ENSO on Antarctic climate is modulated by the phase
69 of SAM, with the signal amplified when SAM and ENSO are atmospherically in phase (positive SAM/La Niña
70 or negative SAM/El Niño) and reduced when they are atmospherically out of phase (positive SAM/El Niño or
71 negative SAM/La Niña) (Clem et al., 2016; Fogt et al., 2011). Positive SAM and La Niña conditions are associated
72 with a deepening (i.e. lower pressure anomaly) ASL, while negative SAM and El Niño conditions weaken the
73 ASL, and influence its longitudinal shift (Raphael et al., 2016a; Hosking et al., 2013). The deepening of the ASL
74 induces continental wind outflow on its western flank, reducing precipitation and SMB over the Antarctic
75 Peninsula and from the Bellingshausen Sea to the Ross Sea region in West Antarctica, whereas a weakened ASL
76 leads to onshore winds that enhance precipitation and SMB (Zhang et al., 2021; Li et al., 2022). The longitudinal
77 shift of the ASL modifies these impact zones.

78 The spatial patterns and magnitude of AIS mass variability due to large-scale modes of climate variability remain
79 unclear. Studies on the role of ENSO in Antarctic climate have mostly focused on precipitation derived from
80 reanalysis products or modelled SMB data (e.g., Medley and Thomas, 2019; Clem et al., 2016; Clem and Fogt,
81 2013; Fogt et al., 2011). Only a few studies have examined the relationship between large-scale modes of climate
82 variability and recent observed ice mass variation using Gravity Recovery and Climate Experiment (GRACE)
83 observed AIS ice mass change time series on timescales ranging from months to decades (e.g., Bodart and
84 Bingham, 2019; Zhang et al., 2021; King et al., 2023). Most of these studies have focused on single strong ENSO
85 events, such as the 2015–2016 El Niño (Bodart and Bingham, 2019), or on the mean impact of ENSO on the AIS.
86 In contrast, our study investigates the spatial impacts of multiple individual ENSO periods (as defined in our
87 study), enabling an assessment of how AIS mass variability differs between events and capturing the diverse
88 responses across the ice sheet, rather than a mean signal.

89 The GRACE mission, launched in 2002, has contributed to our understanding of the redistribution of mass within
90 the Earth system, which is useful for observing changes of the Greenland and Antarctic ice sheets (Tapley et al.,
91 2004; Shepherd et al., 2012). GRACE-observed ice mass variability is related to atmospheric circulation-driven
92 snow accumulation and variation in ice discharge (Diener et al., 2021). Although mass loss from runoff and
93 sublimation is included in the GRACE signal, these components are relatively minor compared to discharge. Over
94 the interannual timescales, atmospheric variability dominates the observed mass changes (King et al. 2023).
95 Studies of ENSO's impact on AIS using GRACE-observed ice mass changes show that different ENSO events
96 result in varying climatic and surface weather effects, leading to different spatial patterns of AIS mass variability.
97 Bodart and Bingham (2019) demonstrated that during the 2015–2016 El Niño, the Antarctic Peninsula and West
98 Antarctica gained mass, while East Antarctica experienced a reduction in mass. This spatial pattern is also
99 consistent over a longer period, in line with Zhang et al. (2021) who found similar correlations. They observed a
100 bipolar spatial pattern: during El Niño events, there was a mass gain over the Antarctic Peninsula and West
101 Antarctica and a mass loss over East Antarctica, while the pattern reversed during La Niña events. The bipolar
102 spatial patterns are consistent with the results of King et al. (2023), based on a GRACE analysis for the period
103 2002–2021, and King and Christoffersen (2024), which used GRACE and altimetry data (2002–2020), despite
104 differences in approaches and study periods. However, other studies have suggested that specific ENSO events
105 and types of ENSO events have distinct impacts on Antarctic SMB that are not limited to a bipolar pattern (e.g.,
106 Macha et al., 2024; Sasgen et al., 2010).

107 This study aims to investigate the spatial patterns of ice mass change and the driving atmospheric circulation
108 conditions during various ENSO-dominated periods, as observed in GRACE-derived AIS mass variations
109 between 2002 and 2022. Since GRACE observes total mass change without distinguishing between the individual
110 components of the mass balance, we use SMB output from a regional climate model RACMO2.4p1 to assess the
111 contribution of SMB to the spatial patterns detected by GRACE. The results indicate that no two ENSO periods
112 have the same net effect on Antarctic ice mass, especially at regional scales, and the bipolar spatial pattern
113 observed in earlier studies is not consistent across all ENSO events. This variability suggests that the ENSO signal
114 in the AIS is shifted from its background pattern depending on event-specific atmospheric and oceanic factors.

115 2. Data and Methods

116 2.1. AIS mass change

117 We used the GRACE and GRACE Follow On data, provided by the GFZ German Research Centre for
118 Geosciences (Landerer et al., 2020). The GRACE Follow-On mission, launched in May 2018, succeeded the
119 GRACE mission, which was decommissioned in October 2017 due to battery and fuel problems. This gap between
120 the GRACE and GRACE Follow-On missions resulted in the loss of data from July 2017 and May 2018. Our
121 analysis involved GRACE data spanning from April 2002 to Dec 2022 without gap filling. We used the COST-G
122 release 1 version 3 (RL-01 V0003) gridded mass anomaly product, which combines GRACE/GRACE-FO
123 solutions from multiple GRACE analysis centres (Landerer et al., 2020). The data are provided on 50 km grid
124 products with approximately monthly temporal sampling. However, GRACE data have an underlying spatial
125 resolution of ~300km (Sasgen et al., 2020; Dahle et al., 2024). This relatively coarse resolution limits GRACE's
126 ability to resolve or capture relatively small mass changes, particularly those associated with localised SMB
127 anomalies.

128 The various available GRACE data products differ based on the processing methods and background models used.
129 The gridded mass change product adopted here is initially derived by solving for spherical harmonic coefficients
130 and then computing mass anomalies for each grid cell across the entire ice sheet using tailored sensitivity kernels
131 that minimise both GRACE and leakage error (Groh and Horwath, 2016). Within this product, glacial isostatic
132 adjustment is corrected using the ICE6G_D model (Peltier et al., 2018), although this has no bearing on non-linear
133 variability as studied here. The effects of atmospheric and oceanic mass redistribution are modelled using standard
134 de-aliasing products. Spherical harmonic degree-1 terms are added based on the approach of Swenson et al.
135 (2008). Further details about the GRACE time series, post-processing techniques, and quality assessment can be
136 found in Dahle et al. (2019). It is worth noting that the GRACE-observed ice mass change time series is affected
137 by systematic errors associated with the GRACE orbital geometry and small unmodelled errors, evident in the
138 (largely north-south) striping pattern observed in some of the ice mass change results.

139 We focus our analysis on the ENSO signal in ice mass variation during different ENSO-dominated periods. First,
140 we removed short-term signal fluctuations in the GRACE data by applying a 7-month moving median smoother
141 to the GRACE time series. This filter choice, following King et al. (2023), is a subjective decision aimed at
142 dampening month-to-month noise without distorting longer-term variability. Since our focus is on GRACE-
143 observed ice mass variability, we subtracted the linear trend at each grid point, estimated using ordinary least
144 squares over the data span. This effectively produces mass anomalies with respect to the 2002–2022 GRACE
145 period.

146 To understand the relationship between ice mass changes and ENSO-dominated periods, we computed the rate of
147 ice mass change for each identified ENSO-dominated period. These rates represent the impact of ENSO during
148 each ENSO-dominated period. We calculated the rates for each grid cell of the gridded GRACE ice mass anomaly
149 data and generated spatial patterns of ice mass trends for each ENSO-dominated period.

150 2.2. Climate indices

151 To characterise ENSO variability, we used the Niño3.4 index, one of several metrics that measures the strength
152 and phase of ENSO based on SST anomalies in the central and eastern tropical Pacific. This index is obtained by
153 tracking the running five-month mean SST based on the HadISST record over 5°N–5°S, 170°W–120°W (Rayner
154 et al., 2003) and is normalised and shown in Fig. 1a. It is provided by the Climate Prediction Centre (CPC) of the
155 National Oceanic and Atmospheric Administration (NOAA) and can be accessed at
156 <https://psl.noaa.gov/data/timeseries/month/Nino34/>. The Niño3.4 temperature anomalies are standard for
157 detecting and monitoring ENSO events but cannot differentiate between eastern and central ENSO events. We
158 used the Niño3.4 index because our focus was on the spatial variability in AIS mass during all ENSO events,
159 rather than differentiating between eastern and central ENSO events.

160 For SAM, we used the station-derived index from Marshall (2003), available at [http://www.nerc-](http://www.nerc-bas.ac.uk/icd/gjma/sam.html)
161 [bas.ac.uk/icd/gjma/sam.html](http://www.nerc-bas.ac.uk/icd/gjma/sam.html), and shown in Fig. 1a. This index is based on the zonal pressure differences at 12
162 stations located between 40° S and 65° S.

163 To identify ENSO signatures in the GRACE data, we first identified El Niño- and La Niña-dominated periods
164 based on the cumulative summed indices, which act as a sort of low-pass filter of the raw indices. The cumulative
165 summed indices were derived from anomalies relative to their climatological mean using a reference window of
166 1971-1999. This period is a well observed period before the commencement of GRACE and is the same as that
167 chosen by King et al. (2023). After the indices were normalised using the mean and standard deviation computed
168 within the reference window, the normalised indices were restricted to the GRACE period, cumulatively summed,
169 detrended, and renormalised.

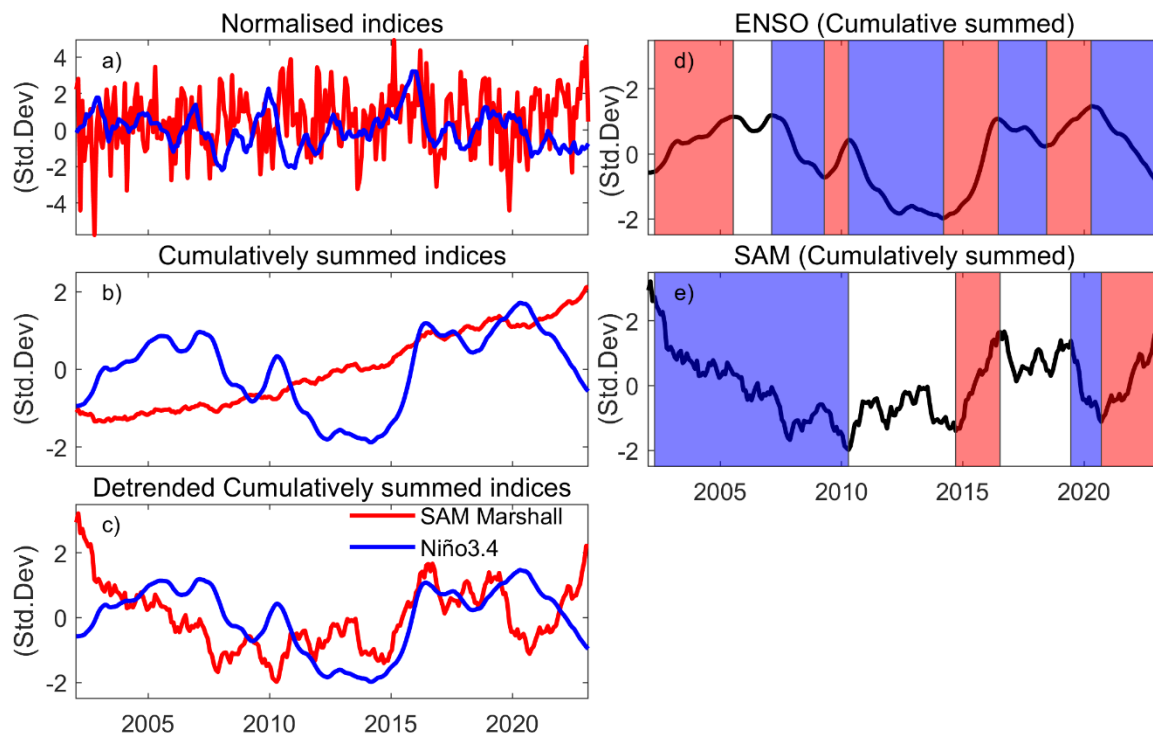
170 To investigate the potential linkage between large-scale climate variability and ice mass variation, we
171 cumulatively summed all the climate indices (Fig 1b) and further detrended them (Fig. 1c). The AIS mass reflects
172 the compound effect of surface mass fluxes over time. The cumulative mass flux observed by GRACE reflects
173 the cumulative climate indices (King et al., 2023) as opposed to raw indices, which relate to mass flux. These
174 cumulative indices are also captured by modelled cumulative SMB (Kim et al., 2020; Diener et al., 2021). The
175 alternative approach is to difference GRACE data in time, but this inflates the GRACE noise and reduces the
176 lower frequency signal and is hence undesirable (King et al., 2023).

177 In this study, we defined El Niño-dominated periods as intervals during which the positive phase of ENSO persists
178 and outweighs the negative phase, culminating in a positive peak in the cumulative ENSO index. Similarly, La
179 Niña-dominated periods are defined as intervals during which negative phase outweighs the positive phase,
180 culminating in a negative peak. Only ENSO periods with a minimum duration of 12 months were considered in
181 our analysis. In a cumulatively summed index, these are expressed as sustained periods of positive (El Niño) or
182 negative (La Niña) slope. Based on this criterion, we identified four El Niño-dominated periods over the GRACE
183 time steps: 2002–2005, 2009–2010, 2014–2016, and 2018–2020 (Fig. 1d). An equal number of La Niña-
184 dominated periods were found, covering 2007–2009, 2010–2014, 2016–2018, and 2020–2022. The strength of
185 the expression of the ENSO signal in the Antarctic climate is modulated by the phase of SAM (Fogt et al., 2011).
186 During the 2002–2005 El Niño-dominated period, the cumulative SAM index was dominated by negative SAM

187 until around 2008 (atmospherically in phase El Niño/-SAM). After 2008, the cumulative SAM index exhibited no
 188 notable trend, indicating a neutral phase. During the 2014–2016 El Niño, cumulative SAM and ENSO indices
 189 were atmospherically out of phase (El Niño/+SAM). SAM shifted to a neutral state during the 2016–2018 La
 190 Niña. SAM and ENSO were atmospherically in phase during the 2018–2020 El Niño (El Niño/-SAM) and 2020–
 191 2022 La Niña (La Niña/+SAM), which is notable as the only time positive SAM and La Niña co-occurred over
 192 the GRACE period (Fig. 1d, e).

193 Note that we do not distinguish between Central Pacific (CP) and Eastern Pacific (EP) El Niño events in our
 194 analysis because our ENSO dominated periods frequently span multiple years. Indeed, examining the cumulative
 195 CP and EP indices shows they are very similar, aside from 2016–2018, and hard to distinguish in an analysis of
 196 GRACE data (Fig. S1b). Our method using the Niño3.4 index encapsulates variations in the tropical spatial pattern
 197 of SST anomalies.

198



199

200 **Figure 1. Monthly climate indices of SAM (Marshall, 2003) and Niño3.4 from 2002–2022: (a) normalised**
 201 **SAM and Niño3.4 indices; (b) normalised cumulatively summed SAM and Niño3.4 indices; (c) detrended,**
 202 **cumulatively summed SAM and Niño3.4 indices (normalised). Periods until positive and negative peaks**
 203 **are reached in the cumulatively summed Niño3.4 are defined as El Niño-dominated and La Niña-**
 204 **dominated periods, respectively, represented as red and blue shaded areas in (d). Similarly, periods until**
 205 **positive and negative peaks are reached in the cumulatively summed SAM index (Marshall, 2003) are**
 206 **defined as SAM-positive and SAM-negative dominated periods, respectively, denoted as red and blue**
 207 **shaded areas in (e). Neutral dominated periods are represented by white shading.**

208 **2.3. SMB model outputs**

209 We used modelled SMB output from the Regional Atmospheric Climate Model RACMO2.4p1 model (Van Dalum
210 et al., 2025; Van Dalum et al., 2024). This model has a horizontal resolution of 11 km and a vertical resolution of
211 40 atmospheric levels. This version of SMB model output is forced by ERA5 reanalysis data at its lateral
212 boundaries and SST and sea ice extent at the sea surface boundary, with data available from 1979 onward.
213 Compared with previous releases, RACMO2.4p1 provides a better representation of SMB process which agree
214 with observation (Van Dalum et al., 2025; Van Dalum et al., 2024). For our study, monthly SMB values truncated
215 to the GRACE period were used, covering Apr 2002 to Dec 2022. To compare with GRACE data, we computed
216 anomalies relative to the 2002–2022 mean and then cumulatively summed them to obtain cumulative SMB
217 anomalies in units of kg m^{-2} . These anomalies were then interpolated to match the GRACE grid spacing and time
218 steps. We detrended the cumulative SMB and performed a regression analysis on these anomalies for each defined
219 ENSO-dominated period.

220 **2.4. Reanalysis climate data**

221 To explore the potential climatic forcing during an ENSO-dominated period, we examined monthly mean ERA5
222 reanalysis model 10 m winds and sea level pressure from 2002 to 2022, with a resolution of 0.25° by 0.25°
223 (Hersbach et al., 2020). Anomalies of 10 m zonal and meridional wind components, as well as sea level pressure,
224 were computed for each grid cell relative to the mean over the GRACE period, for all regions south of 40° S. We
225 then computed anomaly composite means for each ENSO-dominated period. We used ERA5 products instead of
226 RACMO outputs because ERA5 provides broader spatial coverage and is more suitable for capturing large-scale
227 atmospheric circulation patterns, which are critical for analysing ENSO-related teleconnections. Additionally,
228 RACMO is forced by ERA5.

229 **2.5. Definitions of events, periods and anomaly interpretations used in this study**

230 We use the term ‘El Niño- or La Niña-dominated period’ or simply ‘period’ when considering periods of sustained
231 ENSO phase as defined using our cumulatively summed index. In contrast, when comparing to or describing other
232 literature, we use the term ‘El Niño/ La Niña event’ which refers to the peak phase of ENSO events. We also
233 describe anomalies from the mean over the GRACE period. For the purposes of this study, the pressure and wind
234 fields, as well as SMB and GRACE mass change, depicted in the figures represent anomalies from the 2002–
235 2022 period for each relevant variable. That is, for a given wind and pressure map, the fields depict wind and
236 pressure anomalies against the 2002–2022 mean (the GRACE data period). For example, positive anomalies over
237 the Antarctic continent reflect a relative strengthening of the mean Antarctic High, while negative anomalies
238 reflect a relative weakening of the Antarctic High (not the presence of a low). For SMB, positive SMB and
239 GRACE anomalies represent an increase in mass, whereas negative anomalies indicate a reduction in mass relative
240 to 2002–2022.

241 **2.6. Statistical significance of the results**

242 To quantify the significance of our regression trends at each grid point, we employed a two-tailed Student’s t-test.
243 The standard error of the slope at each grid point was calculated from the regression residuals and used to assess
244 whether the slope significantly differed from zero at the 5% significance level. For mean sea level pressure

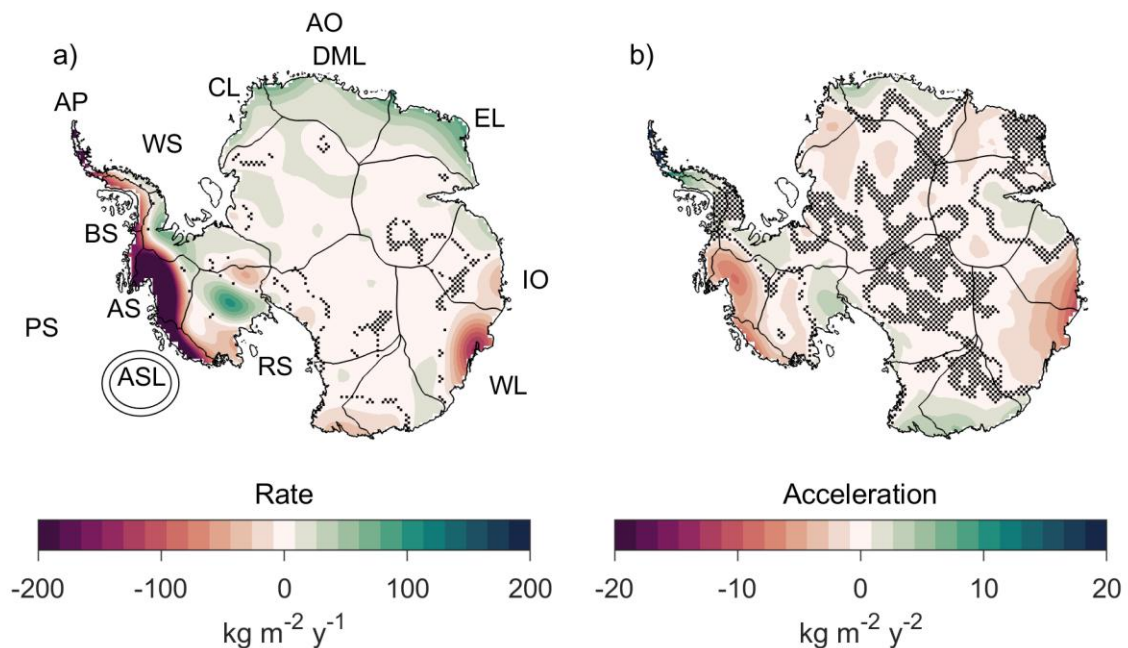
245 anomaly composites, statistical significance was assessed relative to the 2002–2022 baseline using a two-sample
246 *t*-test assuming unequal variances, also at the 5% significance level.

247 3. Results

248 3.1 Ice mass change

249 We start by examining the long-term trend and acceleration in AIS mass change over the GRACE observational
250 period, represented by the linear and quadratic terms in the regression, respectively (Fig. 2). The spatial pattern
251 reveals strong regional variability, with areas of both positive and negative mass anomalies. While not identical,
252 the linear rate and acceleration exhibit closely aligned spatial patterns of mass change. In West Antarctica, the
253 rate of ice mass loss is most pronounced in the Amundsen Sea and Bellingshausen Sea sectors, where accelerated
254 ice discharge is well documented (Rignot et al., 2019; Gardner et al., 2018). The East Antarctic ice sheet shows
255 mass gain across Dronning Maud Land (and through to Enderby Land); conversely, the Wilkes Land sector has
256 experienced a decline in mass. The negative acceleration observed in the Amundsen Sea sector and Wilkes Land
257 indicates that the rate of mass loss in these regions is increasing over time.

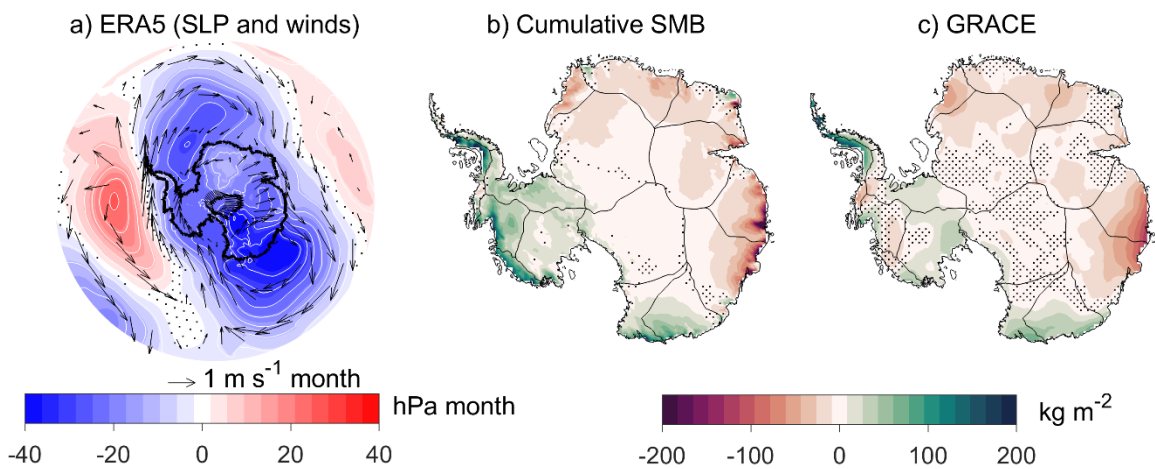
258 While the long-term trend in AIS mass is primarily driven by ice dynamics, the interannual variability is more
259 closely linked to changes in precipitation (Kim et al., 2020). Short-term mass fluctuations can be influenced by
260 large-scale circulation modes. To explore the impact of ENSO on ice mass variability, we next examine how
261 atmospheric circulation and mass anomalies respond to ENSO forcing.



262
263 **Figure 2. a) Linear rate and b) acceleration of AIS mass change (2002–2022) based on GRACE data from**
264 **using univariate regression. Key Antarctic regions are labelled: Antarctic Peninsula (AP), Bellingshausen**
265 **Sea (BS), Amundsen Sea (AS), Amundsen Sea Low (ASL), Pacific Sector (PS), Ross Sea (RS), Indian**

266 Ocean (IO), Atlantic Ocean (AO), Wilkes Land (WL), Enderby Land (EL), Dronning Maud Land
 267 (DML), Coats Land (CL), and Weddell Sea (WS). Stippling indicates areas not statistically significant
 268 ($\rho > 0.05$). Significance tests do not reflect the effects of temporal correlations in these data (Williams et al.,
 269 2014).

270 Figure 3 presents the regression results of cumulatively summed anomalies in ERA5 reanalysis climate variables
 271 (sea level pressure and 10 m winds) and RACMO2.4p1 model SMB, along with GRACE-derived ice mass change
 272 anomalies, against the cumulatively summed Niño3.4 index. All variables were detrended before regression to
 273 focus on the variability. The results show that the cumulative ENSO is associated with shifts in atmospheric
 274 circulation that supports the observed dipole SMB and ice mass anomaly between West and East Antarctica (Fig.
 275 3a)



276
 277 **Figure 3. Regression of cumulatively summed sea level pressure (shaded region and contour) and 10 m**
 278 **wind anomalies represented by reference vectors (m s^{-1}) from ERA5 reanalysis (a), cumulatively summed**
 279 **RACMO2.4p1 model SMB anomalies (b), and GRACE ice mass change anomalies (c) regressed against**
 280 **cumulatively summed Niño3.4. The u and v wind components were regressed separately. All panels**
 281 **reflect regression anomalies over the period 2002–2022. All variables were linearly detrended prior to**
 282 **regression using the full data periods. Stippling indicates regions where the regression results are not**
 283 **statistically significant ($\rho > 0.05$).**

284 We also compared the regression results presented in Figure 3 with El Niño and La Niña composites (see Fig. S2)
 285 derived from annual accumulated SMB anomalies and annual mean Niño3.4 index, which broadly agree with the
 286 cumulative approach spatial patterns observed in West and East Antarctica. From the composite map (Fig. S2,
 287 covering 2002–2022), we observe that in West Antarctica, El Niño years are associated with a positive mean SMB
 288 anomaly ($26.98 \text{ kg m}^{-2} \text{ yr}^{-1}$), while La Niña years correspond to a negative mean anomaly ($-10.29 \text{ kg m}^{-2} \text{ yr}^{-1}$).
 289 In contrast, East Antarctica shows a negative mean SMB anomaly ($-3.14 \text{ kg m}^{-2} \text{ yr}^{-1}$) during El Niño years and a
 290 positive anomaly ($5.28 \text{ kg m}^{-2} \text{ yr}^{-1}$) during La Niña years.

291 Our result shows that, spatially, SMB and ice mass increase in West Antarctica and decrease in East Antarctica
 292 during El Niño-dominated periods, with the pattern reversing during La Niña-dominated periods (Fig. 3b–c). The

293 cumulative ENSO-induced changes in meridional flow are associated with the SMB variability (Fig. 3a–b). Since
294 SMB fluctuations are closely linked to ice mass change, the spatially coherent patterns between SMB and
295 GRACE-derived ice mass change vary (Fig. 3b–c).

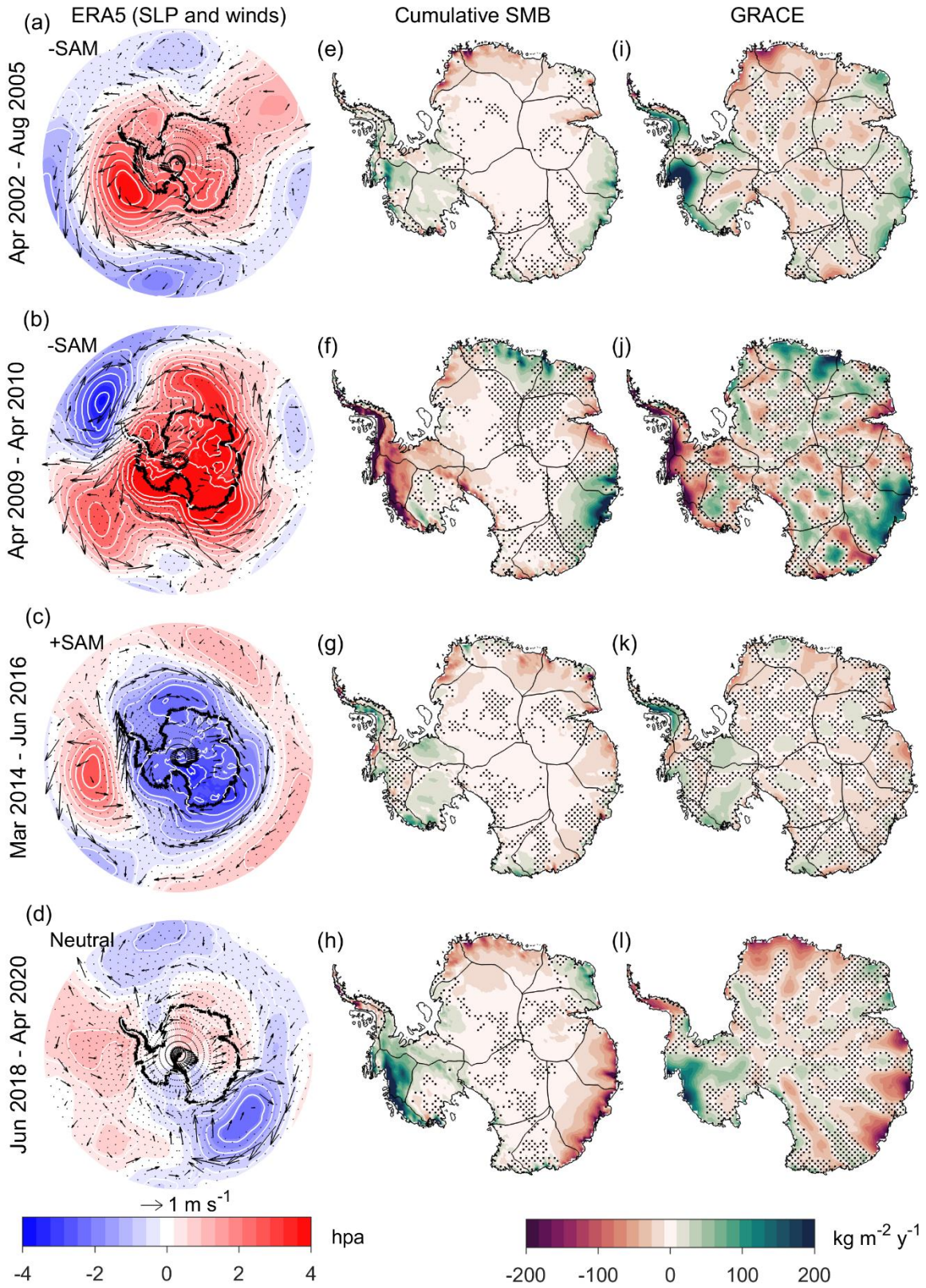
296 However, in West Antarctica, the SMB signal differs from GRACE-derived ice mass changes, which indicates
297 relatively modest positive mass anomalies compared to the stronger SMB signal (Fig. 3b–c), whereas in East
298 Antarctica, the two signals are more closely aligned.

299 We next focus on the variability within ENSO-dominated periods and find that no two ENSO periods are identical.
300 We examine AIS mass change, SMB variability, and the atmospheric circulation driving these changes during
301 different ENSO-dominated periods we defined in this study (see section 2.2). The results reveal distinct spatial
302 patterns of ice mass change associated with individual El Niño and La Niña events. We remind the reader that the
303 GRACE signal is more reliable in the coastal regions and less reliable in the interior, where inherent systematic
304 errors in GRACE measurements in the form of north-south striping are more pronounced.

305 **3.2. El Niño-dominated periods**

306 Across the Antarctic continent, spatial pressure anomalies vary between El Niño-dominated periods, with both
307 positive and negative pressure anomalies observed (Fig. 4a–d). These pressure patterns reflect either a relative
308 intensification or relative weakening of the mean Antarctic High (Fig. 4a–b). These variations align with the
309 cumulatively summed SAM indices (Fig. 1e), where high-pressure anomalies correspond to prolonged negative
310 SAM phases, and low-pressure anomalies coincide with prolonged positive SAM phases. Mass anomalies
311 observed in both RACMO SMB and GRACE are most pronounced along the coastal regions, where the signals
312 are statistically significant. In this study, we focus on the absolute mass changes during each period, while relative
313 impacts are presented in Fig. S3.

El Niño-dominated periods



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315

316

Figure 4. Atmospheric circulation anomalies relative to the GRACE period (2002–2022) (a–d), rate of change in cumulative SMB anomalies from RACMO2.4p1 model (e–h) and linear rate of GRACE-

317 **derived ice mass anomalies (i–l) during El Niño-dominated period. Sea level pressure anomalies are**
318 **shown as shaded regions with contours (hPa), while wind anomalies are indicated by reference vectors**
319 **(m s⁻¹). SMB and GRACE maps (kg m⁻² y⁻¹) illustrate variability in AIS mass for each identified El Niño-**
320 **dominated period. The GRACE signal is more reliable in the coastal regions and less reliable in the**
321 **interior, where GRACE systematic error in the form of north-south striping is more evident. Non-**
322 **significant areas are stippled for the pressure anomalies and AIS mass trend at p-value>0.05.**
323

324 **3.2.1. West Antarctic anomalies during El Niño-dominated periods**

325 In West Antarctica, El Niño-dominated periods are characterised by a positive pressure anomaly in the Pacific
326 sector off the West Antarctic coastline (Fig. 4a–b). The position and strength of these positive pressure anomalies
327 vary for each El Niño-dominated period, which is also reflected in the variation of wind anomalies and spatial
328 patterns of SMB (Fig. 4e–h) and ice mass change (Fig. 4i–l). However, during the 2018–2020 period, no
329 significant pressure anomaly is observed, and in the 2009–2010 period, a significant pressure anomaly is located
330 closer to the continent, with a non-significant pressure anomaly further north (Fig. 4a–b).

331 During three out of four El Niño-dominated periods (2002–2005, 2014–2016, and 2018–2020), the Amundsen
332 Sea sector shows positive anomalies in both SMB (Fig. 4e, g–h) and ice mass anomalies (Fig. 4i, k–l), indicating
333 mass gain, despite variations in the location and strength of the positive pressure anomaly in the Pacific (Fig. 4a,
334 c–d). The positive mass anomalies are more widespread across the Amundsen Sea sector during the 2002–2005
335 period in GRACE (Fig. 4i) and in both SMB and GRACE during the 2018–2020 period (Fig. 4h, l). The positive
336 pressure anomaly in the Pacific which supports these mass gains, is significant during the 2002–2005 period.

337 For the 2014–2016 El Niño-dominated period, we observed weak and, in some regions, non-significant positive
338 SMB and ice mass anomalies in the Amundsen Sea sector and western Ross Sea (Fig. 4g, k). During this period,
339 our cumulative ENSO and SAM were out of phase (El Niño/+SAM), as evidenced by significant negative pressure
340 anomalies over the continent (Fig. 4c). The positive pressure anomaly in the Pacific was located away from the
341 coastline and was associated more with wind anomalies along the shore, rather than onshore (Fig. 4c).

342 The mass change pattern in the Amundsen Sea sector during the 2009–2010 El Niño-dominated period is distinct
343 from the other El Niño periods, with widespread significant negative SMB (Fig. 4f) and ice mass (Fig. 4j)
344 anomalies indicating a net mass reduction. In contrast to the other El Niño periods, a large area of significant
345 positive pressure anomaly extends offshore from the Antarctic continent, spanning from the Peninsula to beyond
346 the Ross Sea, and supports offshore wind anomalies in the Amundsen Sea sector (Fig. 4b).

347 The Antarctic Peninsula exhibits contrasting mass change responses during El Niño-dominated periods (Fig. 4).
348 Positive SMB (Fig. 4e, g) and ice mass anomalies (Fig. 4j, l) are observed during the 2002–2005 and 2014–2016
349 El Niño periods, particularly in GRACE (Fig. 4i, k), whereas negative SMB (Fig. 4f, h) and ice mass anomalies
350 (Fig. 4j, l) are evident during the 2009–2010 and 2018–2020 periods. These mass change pattern align with
351 pressure anomaly distributions and are associated with onshore wind anomalies during the 2002–2005 and 2014–
352 2016 periods (Fig. 4a, c) and offshore wind anomalies for 2009–2010 and 2018–2020 (non-significant) periods
353 (Fig. 4b, d).

354 **3.2.2. East Antarctic anomalies during El Niño dominated periods**

355 In the Atlantic Ocean sector, three out of four El Niño-dominated periods (2002–2005, 2014–2016, and 2018–
356 2020) show consistent patterns with negative SMB (Fig. 4e, g–h) and ice mass (Fig. 4i, k–l) anomalies in Dronning
357 Maud Land. The reduction in mass is more extensive during the 2002–2005 and 2018–2020 El Niño periods,
358 covering much of Coats Land and Dronning Maud Land, with strong mass anomalies along the western edge of
359 Dronning Maud Land (Fig. 4e, h, i, l). The magnitude of mass reduction is lesser for the 2014–2016 El Niño
360 period (Fig. 4g). However, among these periods, the 2014–2016 El Niño period shows a significant pressure
361 anomaly, which can be directly associated with the observed mass reduction patterns.

362 Conversely, during the 2009–2010 El Niño period, we observed a significant anomalous mass gain in Dronning
363 Maud Land (Fig. 4f, j). This mass gain coincides with a significant positive pressure anomaly over the Atlantic,
364 which supports onshore wind anomalies into Dronning Maud Land.

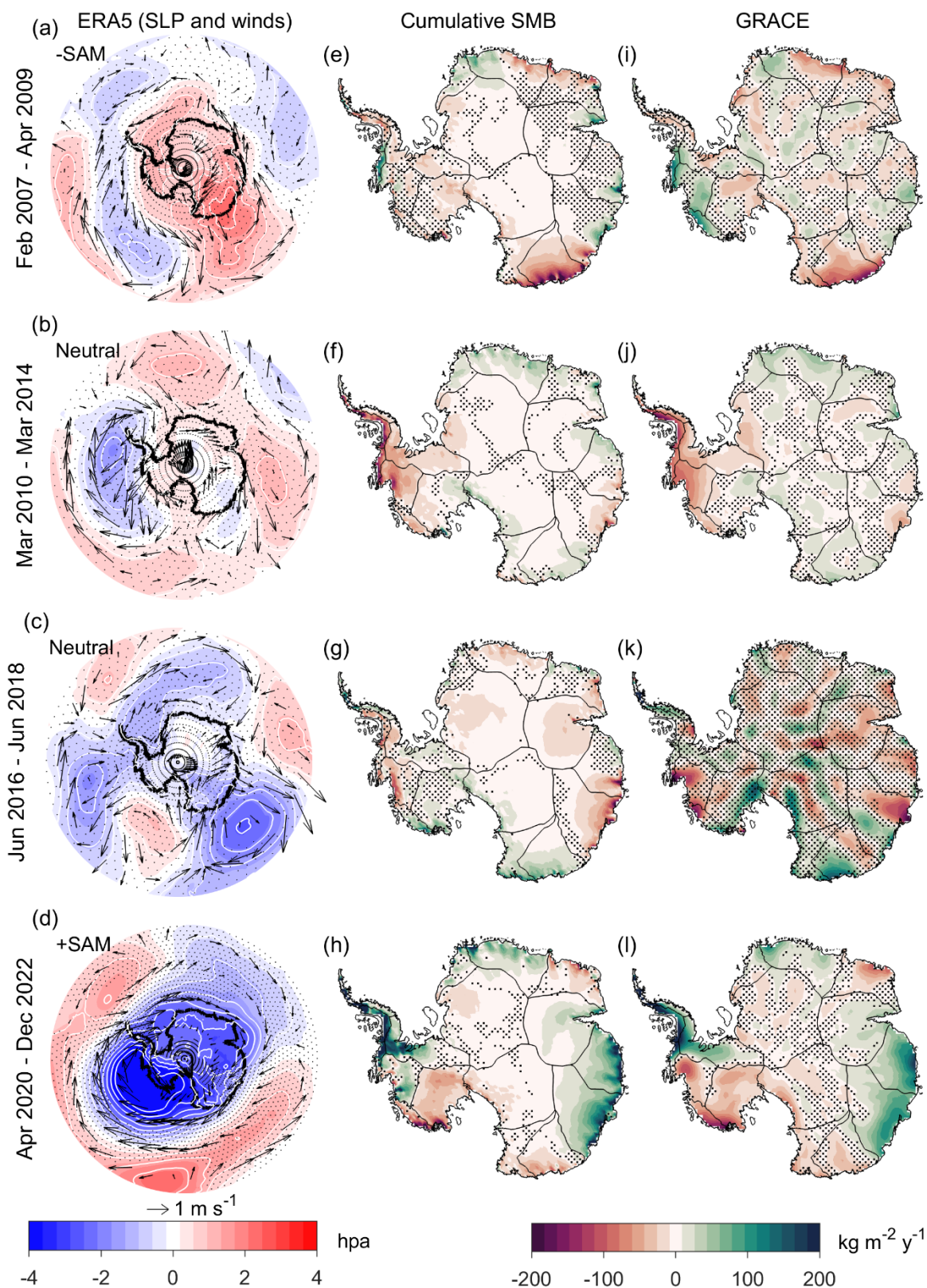
365 Enderby Land shows positive mass anomalies, which in some instances are evident in GRACE but not in SMB,
366 and vice versa. For example, during the 2002–2005 El Niño period, positive mass anomalies are more pronounced
367 in GRACE than in SMB (Fig. 4e, i), whereas during the 2018–2020 El Niño period, the positive anomalies are
368 stronger in SMB than in GRACE (Fig. 4h, l). Atmospheric circulation anomalies during the 2009–2010 and 2014–
369 2016 El Niño periods are statistically significant and supports the observed mass change patterns. For the 2002–
370 2005 and 2018–2020 El Niño periods, we cannot associate the observed mass patterns to circulation anomalies at
371 the 0.05 significance level.

372 In the Indian Ocean sector/Wilkes Land, mass gain is broadly observed during the 2002–2005 and 2009–2010 El
373 Niño periods (Fig. 4e–f, i–j), and a reduction in mass during the 2014–2016 and 2018–2020 El Niño periods (Fig.
374 4g–h, k–l). During the periods with mass gain, positive pressure anomalies were present over Wilkes Land (Fig.
375 4a–b), with the anomaly more intense and statistically significant during the 2009–2010 El Niño period and
376 associated with a greater magnitude of mass gain in Wilkes Land (Fig. 4b, f, j). Conversely, during periods broadly
377 associated with mass reduction (Fig. 4g–h, k–l), negative pressure anomalies were observed around the Wilkes
378 Land region, aligned with offshore wind anomalies across much of the sector (Fig. 4c–d).

379 **3.3. La Niña-dominated periods**

380 Figure 5 presents atmospheric circulation patterns, SMB anomalies, and AIS mass changes during La Niña-
381 dominated periods. Absolute mass changes are shown in this section, while relative mass changes can be found
382 in Fig. S4. The atmospheric circulation pattern anomalies during La Niña-dominated periods (Fig. 5a–d) shows
383 fewer areas of statistical significance compared to the El Niño periods (Fig. 4a–d). Instrument malfunctions and
384 the termination of the GRACE mission in 2017 introduced noise and data gaps, affecting ice mass estimates.
385 Therefore, we limit our discussion to the atmospheric circulation and SMB for the 2016–2018 La Niña-dominated
386 period to avoid conclusions based on potentially unreliable data in GRACE.

La Niña-dominated periods



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Figure 5. Atmospheric circulation anomalies relative to the GRACE period (2002–2022) (a–d), rate of change in cumulative SMB anomalies from the RACMO2.4p1 model (e–h), and linear rate of GRACE-

390 derived ice mass anomalies (i–l) during La Niña-dominated period. Sea level pressure anomalies are
391 shown as shaded regions with contours (hPa), 10 m wind anomalies are indicated by reference vectors
392 (m s^{-1}). SMB and GRACE ($\text{kg m}^{-2} \text{y}^{-1}$) maps illustrate variability in AIS mass for each identified La Niña-
393 dominated period. The GRACE signal is strongest near the coastal regions and weaker in the interior,
394 where uncertainties are higher. The GRACE satellite malfunction during 2016–2018 is apparent in the
395 signal for that period, where instrument noise dominates over actual variability with pronounced north-
396 south striping. Non-significant areas are stippled for the pressure anomalies and AIS mass trend at p-
397 value>0.05.
398

399 3.3.1. West Antarctic anomalies during La Niña-dominated periods

400 Overall, during our La Niña-dominated periods, the Pacific sector exhibits a persistent negative pressure anomaly
401 (Fig. 5a–d), which appears more elongated than the positive pressure anomaly associated with El Niño periods.
402 This pressure anomaly is statistically significant for the 2020–2022 La Niña period; however, there are also
403 significant regions near the centre of the pressure anomaly during the 2010–2014 La Niña period.

404 Three out of the four La Niña periods (2010–2014, 2016–2018, and 2020–2022) are broadly associated with
405 negative SMB (Fig. 5f–h) and ice mass anomalies (Fig. 5j–l) across the Amundsen Sea sector. The reduction in
406 mass during the 2020–2022 and 2010–2014 La Niña periods aligns with a significant negative pressure anomaly
407 in the Pacific sector, and offshore wind anomalies (Fig. 5b, d).

408 In contrast, during the 2007–2009 La Niña period, a mass gain is prominently observed in GRACE (Fig. 5i), a
409 pattern more commonly associated with El Niño periods described earlier. However, the SMB and pressure
410 anomaly patterns during this period are not statistically significant at the 0.05 level.

411 Similar to the Amundsen Sea sector, the Antarctic Peninsula exhibits contrasting mass change responses during
412 La Niña-dominated periods. Broadly, negative mass anomalies are observed during the 2007–2009 and 2010–
413 2014 La Niña periods (Fig. 5i–j), whereas positive mass anomalies are evident during the 2016–2018 and 2020–
414 2022 La Niña periods (Fig. 5k–l). The magnitude of mass reduction is strongest during the 2010–2014 La Niña
415 period, while the mass gain is most pronounced during the 2020–2022 La Niña period.

416 This contrasting mass change response between the two periods aligns with the position of the negative pressure
417 anomaly in the Pacific sector. In the 2010–2014 La Niña period, the pressure anomaly is centred over the
418 Bellingshausen Sea, accompanied by offshore wind anomalies over the Peninsula (Fig. 5b). In contrast, during
419 the 2020–2022 La Niña period, the negative pressure anomaly is centred in the Amundsen Sea, with onshore wind
420 anomalies directed into the Peninsula (Fig. 5d).

421 3.3.2. East Antarctic anomalies during La Niña-dominated periods

422 Along the Atlantic sector, a dipole-like mass anomaly pattern is present during the 2007–2009 and 2020–2022 La
423 Niña periods (Fig. 5e, h), whereas a more uniform response is observed during the 2010–2014 and 2016–2018 La
424 Niña periods (Fig. 5f–g). During the 2007–2009 La Niña period, positive SMB anomalies were observed over

425 Coats Land and negative SMB anomalies toward Enderby Land (Fig. 5e), with this spatial pattern reversed during
426 the 2020–2022 La Niña period (Fig. 5h).

427 Positive mass anomalies were also observed across the Atlantic region during the 2014–2016 La Niña period,
428 with a reversed pattern during the 2016–2018 La Niña period (Fig. 5f–g). Regionally, Dronning Maud Land shows
429 consistent positive SMB (Fig. 5f, h) and ice mass anomalies (Fig. 5j, l) during the 2010–2014 and 2020–2022 La
430 Niña periods.

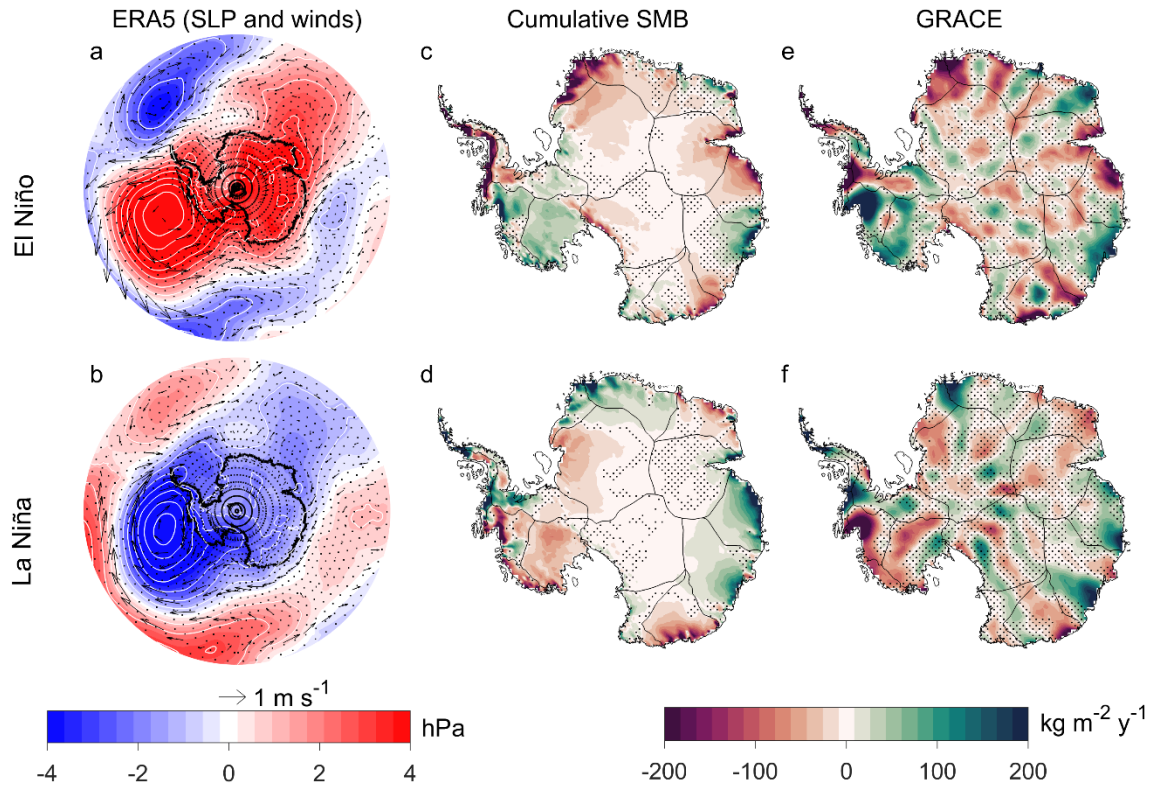
431 The negative pressure anomaly during the 2020–2022 La Niña period aligns with the observed mass gain in
432 Dronning Maud Land. Conversely, during the 2016–2018 period, negative SMB anomalies were observed in
433 Dronning Maud Land, with no clear pressure anomaly pattern (Fig. 5g).

434 In the Indian Ocean sector/Wilkes Land we found no consistent mass response to La Niña-dominated periods.
435 During the 2020–2022 La Niña period, mass change in the Indian Ocean sector is spatially uniform, with positive
436 mass anomalies observed across the entire region (Fig. 4h, l). This contrasts with other La Niña periods, which
437 show more variable responses. The 2010–2014 and 2016–2018 La Niña periods are consistent with each other,
438 showing negative mass anomalies over Wilkes Land. For both periods, a negative pressure anomaly is present
439 adjacent to the Wilkes Land coast, with the 2016–2018 period showing a statistically significant anomaly and
440 stronger negative mass signals. In contrast, the 2007–2009 and 2020–2022 La Niña periods are associated with
441 positive mass anomalies in Wilkes Land (Fig. 5i, l), although the anomalies during 2007–2009 are weaker and
442 less spatially extensive (Fig. 5i). During the 2007–2009 La Niña period, a positive pressure anomaly marginally
443 significant at the centre of the anomaly extends offshore along the Wilkes Land coast, associated with onshore
444 wind anomalies (Fig. 5a).

445 **3.4. Mean Anomalies during ENSO-dominated periods**

446 Figure 6 presents the mean AIS response across El Niño- and La Niña-dominated periods, summarizing the
447 impacts of different ENSO periods. The figure is derived by averaging the maps presented in Figures 4 and 5.
448 While this mean response differs slightly from the regression results in Fig. 3b–c, certain regional patterns remain
449 consistent. The SMB results show a positive response during El Niño-dominated periods in the Amundsen Sea
450 sector and Marie Byrd Land, as well as in Enderby Land (Fig. 6c). In contrast, negative SMB anomalies are
451 observed in the Antarctic Peninsula, Coats Land, and Dronning Maud Land (Fig. 6c). During La Niña-dominated
452 periods, this pattern is broadly reversed (Fig. 6d). Wilkes Land shows positive SMB anomalies during both El
453 Niño- and La Niña-dominated periods; however, the anomalies are more spatially extensive during La Niña (Fig.
454 6c–d). The patterns in GRACE are broadly similar to the SMB results, however, north south stripping noise in
455 GRACE is maximised over short periods.

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Figure 6. The composites are generated based on the results of the four defined ENSO-dominated periods combined. ERA5 mean sea level pressure and 10 m wind anomalies (a–b), RACMO2.4p1 SMB (c–d), and GRACE-derived ice mass change (e–f). This represents the cumulative impact of different ENSO phases on AIS mass variability. Sea level pressure anomalies are shown as shaded regions with contours (hPa), and 10 m wind anomalies as vectors (m s^{-1}). SMB and GRACE data ($\text{kg m}^{-2} \text{y}^{-1}$) are shown. Non-significant areas are stippled at $p\text{-value} > 0.05$.

465 4. Discussion

466 4.1 Continental-wide perspective

467 We examined the AIS mass variability during different ENSO-dominated periods. Our results show that the AIS
468 exhibits considerable variability across these periods, each associated with its own circulation anomalies (Figs. 4,
469 5), influenced by interactions between ENSO and SAM (Hosking et al., 2013; Fogt et al., 2011). Over longer
470 timescales, the mean response reveals a dipole pattern: positive mass anomalies in West Antarctica and negative
471 anomalies in East Antarctic during El Niño periods, and vice-versa during La Niña periods (Fig. 3b–c). This
472 pattern is supported by data-driven analysis showing a strong correlation between GRACE and cumulative ENSO
473 indices (King et al., 2023).

474 However, there is a difference between the SMB signal and GRACE in West Antarctica, but they are closely
475 aligned in East Antarctica (Fig. 3b–c). This suggests that SMB variability drives ice mass changes in East
476 Antarctica, but not necessarily in West Antarctica. The difference may be due to the near-instantaneous response

477 of ice dynamics to ENSO-driven oceanic forcing and/or mismodelled SMB (IMBIE Team, 2018; Rignot et al.,
478 2019), with the latter being more likely (King and Christoffersen, 2024).

479 Averaging multiple ENSO-dominated periods can obscure variability associated with individual periods and lead
480 to misinterpretation. As shown in Figs. 4e–h and 5e–h, mass variability—particularly in the Antarctic Peninsula
481 and East Antarctica—varies significantly across individual ENSO events (Figs. 4, 5). The mean response fails to
482 capture these short-term variations, which are critical for understanding their influence on AIS mass balance.

483 **4.2 West Antarctica**

484 El Niño-and La Niña-dominated periods correspond to positive and negative pressure anomalies in the Pacific,
485 respectively, indicative of positive PSA-1 and negative PSA-1 patterns (Hoskins and Karoly, 1981). These
486 patterns are associated with a weakened or strengthened ASL, influencing circulation and climate in West
487 Antarctica (Raphael et al., 2016b; Turner et al., 2017; Turner et al., 2012). Positive ice mass anomalies in the
488 Amundsen Sea sector during the 2002–2005, 2014–2016 and 2018–2020 El Niño periods (Fig. 4i, k–l) and
489 negative anomalies during the 2010–2014 and 2020–2022 La Niña periods (excluding the 2016–2018 period due
490 to noisy GRACE data) (Fig. 5i, k–l), are broadly consistent with previous studies (Paolo et al., 2018; King et al.,
491 2023). These mass anomalies are supported by the variability in the ASL during El Niño and La Niña periods
492 influencing circulation into the Amundsen Sea sector.

493 During El Niño conditions, a weakened ASL and reduced coastal easterlies allow westerly wind anomalies to
494 bring marine air masses, onshore, which, enhance snowfall and mass accumulation through orographic lifting
495 (Paolo et al., 2018; Huguenin et al., 2024). In contrast, La Niña conditions strengthen the ASL and intensify
496 coastal easterlies, limiting moisture transport and reducing precipitation (Huguenin et al., 2024; Hosking et al.,
497 2013).

498 However, the 2009–2010 El Niño period deviates from this pattern, with negative SMB anomalies observed in
499 the Amundsen Sea sector (Fig. 4f). The pressure anomaly during this period is distinct, with a positive pressure
500 anomaly extending from the Amundsen Sea to beyond the Ross Sea. An important difference to the other El Niño
501 periods, is the extension of this positive pressure anomaly further to the west, which decreases moisture transport
502 into the region. This period encompasses a strong Central Pacific El Niño event (Kim et al., 2011), and associated
503 pressure anomaly (Fig. 4b) resembles patterns linked to such events, which are associated with moisture depleted
504 wind anomalies and suppressed precipitation in the Amundsen and Bellingshausen regions (Chen et al., 2023;
505 Macha et al., 2024).

506 Our 2009–2010 El Niño mass pattern aligns with Macha et al. (2024), who reported reduced accumulation during
507 Central Pacific El Niño events in the SON and JJA seasons. These similarities suggest that the observed mass
508 change may reflect the impact of Central Pacific El Niño phases during the SON and JJA seasons in the Amundsen
509 Sea sector.

510 It is important to state that our defined ENSO periods do not distinguish between El Niño types or seasonal phases
511 but instead capture the net mass change over the entire period, providing broader context for ice sheet mass
512 balance.

513 Similarly, the 2007–2009 La Niña period shows a mass pattern that contrasts with other La Niña periods, featuring
514 a positive mass anomaly in the Amundsen Sea sector (Fig. 5i). However, atmospheric circulation patterns during
515 this period do not statistically support the observed mass gain, suggesting that it may be linked to unrelated
516 weather events or other modes of climate variability.

517 Our results support that mass variability in the Antarctic Peninsula is variable and influenced by various factors
518 such as large-scale climate modes including SAM and ENSO (Clem et al., 2016; Clem and Fogt, 2013) and the
519 Peninsula's unique mountainous geography. A previous study demonstrated a reduction in mass during El Niño
520 and an increase during La Niña across the Peninsula (Sasgen et al., 2010). This is consistent with our results for
521 the 2018–2020 El Niño- and 2020–2022 La Niña-dominated periods (Figs. 4l, 5l). Meanwhile, other studies
522 suggest the opposite pattern, reporting an increase in mass during El Niño and a reduction during La Niña in the
523 Peninsula (Zhang et al., 2021), which aligns with our observed ice mass change during the 2002–2005 and 2014–
524 2016 El Niño periods (Fig. 4i, k) and 2010–2014 La Niña period (Fig. 5j). However, the variable impact appears
525 to be influenced by the position and orientation of the ASL and its effect on moisture transport into the Peninsula
526 (Raphael et al., 2016a). Further, moisture transport into the Peninsula is influenced by SAM-driven westerly winds
527 and ENSO-related meridional flow (Orr et al., 2008; Clem et al., 2016), which contributes to the complex mass
528 change patterns.

529 **4.3 East Antarctica**

530 El Niño and La Niña events have been linked to negative and positive cumulative mass anomalies, respectively
531 in the East Antarctic Ice Sheet (King et al., 2023; Li et al., 2022), consistent with our earlier findings (Fig. 3b–c).
532 Our 2014–2016, 2018–2020 El Niño periods (Fig. 4k–l) and 2010–2014, 2020–2022 La Niña periods (Fig. 4j, l)
533 broadly align with this pattern. However, this pattern is consistent for every ENSO period (e.g., Figs. 4j, 5i), and
534 in some periods regionally variable responses observed across the Atlantic and Indian Ocean sectors.

535 SMB anomalies in East Antarctica are primarily influenced by the strength and position of cyclonic and
536 anticyclonic anomalies over the continent and the Southern Ocean (Figs. 4a–d and 5a–d). These pressure
537 anomalies regulate atmospheric circulation, with meridional flow changes affecting heat and moisture distribution
538 across the region (Scarchilli et al., 2011; Wang et al., 2024; Udy et al., 2021). The SAM phase largely governs
539 these pressure patterns by modulating their positioning which further highlights the dominant role of SAM as a
540 climate driver of mass change in East Antarctica (Fogt et al., 2012; Fogt and Marshall, 2020a; Marshall et al.,
541 2013). For instance, 2014–2016 El Niño showed a mass change pattern that is consistent with a positive SAM
542 phase, with a reduction in precipitation (Marshall et al., 2017) and observed negative mass anomaly (Fig. 4g).

543 The anomalous mass gain during the 2009–2010 El Niño period observed in Dronning Maud Land has been
544 attributed to atmospheric blocking, which produced large episodic snowfall events (Boening et al., 2012).
545 Similarly, a positive pressure anomaly in the Atlantic during the 2010–2014 La Niña period (although not
546 significant at $p < 0.05$ over the 4-year period) appears to support the mass gain in Dronning Maud Land (Fig. 5j).
547 Atmospheric blocking favours the occurrence of atmospheric rivers reaching the Antarctic coastline, often
548 associated with increased precipitation and temperature (Wille et al., 2021; Pohl et al., 2021). The weakening of
549 the westerlies during negative SAM conditions (Clem et al., 2016), allows for Rossby wave amplification and an

550 increased frequency of atmospheric blocking events in East Antarctica, particularly during winter, when the
551 relationship is strongest (Wang et al., 2024). It is important to note that climate modes of variability can create
552 conditions favourable for atmospheric river events in East Antarctica (Shields et al., 2022), especially in Wilkes
553 Land (Wang, 2023). However, in Dronning Maud Land, atmospheric rivers explain about 77 % of interannual
554 variability (Baiman et al., 2023).

555 Our 2002–2005 and 2009–2010 El Niño periods, along with the 2007–2009 La Niña period, show a blocking
556 pattern around Wilkes Land, consistent with transient meridional blocking associated with increased precipitation
557 along the coastline (Udy et al., 2022; Udy et al., 2021). However, given the duration of our defined periods, this
558 transient blocking is likely smoothed out over longer timeframes, which may explain the stronger signal observed
559 during the shorter 2009–2010 El Niño period. The asymmetric shape of the positive pressure anomaly extension
560 off the Wilkes Land is much stronger in the 2009–2010 period, and is consistent with the development of
561 atmospheric blocking in the Tasman Sea region (Pook et al., 2006), which is associated with increased
562 precipitation in Wilkes Land (Pohl et al., 2021; Udy et al., 2022).

563 Our 2020–2022 La Niña period shows significant mass gain across the Indian Ocean and Wilkes Land region and
564 was the only period in our analysis combining La Niña with positive SAM (Fig. 1c). However, this period also
565 included the March 2022 atmospheric river event, which delivered record-breaking precipitation and heat to East
566 Antarctica (Wille et al., 2024). While this event was not the only atmospheric river to occur during the GRACE
567 period, this four-day event likely influenced the mass anomaly patterns of the 2020–2022 La Niña period. To
568 determine the extent of the influence of this event, we examined the 2020–2022 period by comparing the inclusion
569 and exclusion of the March 2022 event (Fig. S5). While the March 2022 event increased the strength of the SMB
570 positive anomaly in Wilkes Land, the region still observed a strong positive SMB anomaly during the 2020–2022
571 period when March 2022 was excluded (Fig. S5). According to Wang et al. (2023), extreme events in October
572 2021 and March 2022 accounted for approximately 38% of the precipitation anomalies in Wilkes Land during the
573 2020–2022 La Niña period, driven by a pair of symmetrically distributed high–low pressure systems over the
574 Southern Ocean near 120°W and 60°E.

575 Our findings indicate that ice mass changes during ENSO-dominated periods cannot be solely attributed to ENSO
576 forcing. To quantify changes in ENSO variability, long-term time series must be considered in future studies
577 (Stevenson et al., 2010), along with the use of climate models to better isolate and capture purely ENSO-driven
578 signals.

579 **4.4 Combined ENSO and SAM influence**

580 Isolating the ENSO signal and its impact on AIS ice mass is challenging due to several factors. The Rossby wave
581 propagation of the ENSO signal to Antarctica is influenced by SAM (Marshall, 2003; Fogt and Marshall, 2020b),
582 and the ENSO signal can be masked by other climate modes, such as zonal-wave 3—a quasi-stationary pattern in
583 the southern high latitudes that affects meridional heat and momentum transport (Goyal et al., 2022; Raphael,
584 2004). Additionally, synoptic-scale weather systems can further mask ENSO’s influence. The complex interaction
585 between ENSO and other modes of climate variability likely drives the equally complex patterns of AIS ice mass
586 change observed during different ENSO-dominated periods.

587 Pressure anomaly variability in the Pacific sector during ENSO-dominated periods can be associated with the
588 cumulative SAM phase. During ENSO periods when the cumulative SAM and ENSO occur in phase (El Niño/–
589 SAM or La Niña/+SAM) (Fogt et al., 2011), the pressure anomaly over the Pacific sector is close to the continent,
590 spatially extensive, and centred around the Amundsen Sea sector (Figs. 4a and 5d). However, during ENSO-
591 dominated periods that are out of phase with the cumulative SAM (El Niño/+SAM or La Niña/–SAM) (Fogt et
592 al., 2011), the pressure anomaly appears northward, away from the continent (Figs. 4c and 5a). Periods where the
593 cumulative SAM index shows a neutral phase, the pressure anomaly in the Pacific is centred around the
594 Bellingshausen Sea sector (Figs. 4d, 5b–c). However, between 2000 and 2020, shifts in large-scale circulation,
595 particularly in SAM, have been reported, potentially affecting ENSO teleconnections and their influence on AIS
596 variability (Xin et al., 2023).

597 Our analysis, which uses cumulative summed indices to match GRACE mass time series, has limitations. It
598 focuses primarily on low-frequency variability and does not account for shorter temporal scale impacts, such as
599 tropical convection pulses that trigger the Rossby waves or high-frequency variability associated with storm
600 systems such as atmospheric rivers. However, the net effect of these would be captured by GRACE.

601 Studies on precipitation (Marshall et al., 2017) and ice core records (Medley and Thomas, 2019) both recognise
602 that SMB generally decreases during positive SAM phase and increases during negative SAM phase. Regarding
603 the impact of SAM on basal melting, negative SAM periods generally decrease the transport of warm circumpolar
604 deep water onto the continental shelf (Palóczy et al., 2018), largely reducing ice shelf basal melt (Verfaillie et al.,
605 2022) and subsequently contributing to ice mass gain. However, the timescale of the upstream ice response of the
606 upstream to positive SAM forcing is unclear and would involve a substantial lag, which can range from months
607 to several years depending on regional ice dynamics (King and Christoffersen, 2024). This suggests that GRACE-
608 derived signals may represent a delayed response rather than an immediate reaction to SAM variability. The spatial
609 pattern of ice mass change anomaly during the 2002–2005 El Niño and 2007–2009 La Niña-dominated periods
610 in the Amundsen Sea sector and Wilkes Land resembles the negative SAM spatial pattern reported by King et al.
611 (2023). Negative SAM dominates the cumulative summed SAM (Fig. 1e) from the start of the GRACE time series
612 in 2002 until around 2010, which aligns with the positive pressure anomaly observed over Antarctica, reflecting
613 a stronger than average (over the GRACE period) Antarctic High during this period (Figs. 4a–b and 5a).
614 Therefore, it is possible that ice mass variability observed between 2002 and 2010 was more influenced by SAM
615 than by ENSO.

616 Our findings agree with the premise that ENSO forcing on the Antarctic climate impacts atmospheric circulation
617 patterns, altering the ASL variability, which in turn influences Antarctic ice mass variability (Zhang et al., 2021;
618 Paolo et al., 2018; Sasgen et al., 2010; Clem et al., 2017). However, across individual ENSO periods, the AIS
619 response exhibits considerable variability, with each period associated with distinct atmospheric circulation
620 patterns. It is possible that the teleconnection between tropical ENSO signals and Antarctic climate may not be
621 fully established during a given ENSO phase or masked by other processes. Our analysis, which uses cumulative
622 summed indices to match GRACE mass time series, is primarily sensitive to low-frequency variability and does
623 not resolve shorter-term impacts, such as tropical convection pulses that initiate Rossby wave trains or high-

624 frequency variability linked to storm systems like atmospheric rivers. Nonetheless, the integrated effect of these
625 processes is captured by GRACE. Additionally, internal dynamics of the ASL may contribute to AIS mass
626 variability that is independent of the influence of ENSO and SAM which potentially can impact our analysis.
627 Given that our analysis spans a 22-year period, it is insufficient to capture the full range of ENSO variability,
628 which requires a longer time period to be fully represented (Stevenson et al., 2010). Future studies should therefore
629 consider a longer record, together with climate models, to better isolate and capture purely ENSO-driven signals.
630 While ENSO induced circulation affects Antarctic SMB (Kim et al., 2020), recent Antarctic ice mass trends
631 (2003–2020) have been primarily driven by mass imbalance triggered by long-term ice dynamics changes (Kim
632 et al., 2024; Rignot et al., 2019). Some of the low-frequency mass variability around the long-term trend (which
633 we removed) is associated with changing ice dynamics. This dynamic signal is stronger in West than in East
634 Antarctica (Rignot et al., 2019).

635 In a warming climate, future ENSO event variability is predicted to increase (Cai et al., 2021). CMIP5 model
636 simulations suggest a reduction in El Niño-induced precipitation over West Antarctica (Lee et al., 2023). Given
637 that SAM is projected to remain in its positive phase across all seasons due to greenhouse gas emissions (Arblaster
638 and Meehl, 2006), accurate modelling of future AIS mass estimates in relation to ENSO teleconnections must
639 account for the interaction between SAM and ENSO. The AIS mass gain observed during 2020–2022 raises
640 questions about how the AIS will respond to future La Niña and positive SAM periods and if it would increase
641 the frequency of extreme events.

642 **5 Conclusion**

643 To examine the AIS mass change during different ENSO-dominated periods, we analysed AIS mass change
644 anomalies observed by GRACE/GRACE-FO spanning the period 2002–2022. These anomalies were interpreted
645 alongside RACMO2.4p1 modelled SMB and mean sea level pressure and 10 m winds from ERA5 reanalysis
646 products. Our analysis reveals that El Niño and La Niña periods exert distinct influences on the AIS, with
647 considerable spatial variability.

648 At the continental scale, three out of the four El Niño-dominated periods were characterised by mass increase in
649 West Antarctica and mass decrease in East Antarctica. Conversely, two out of the three La Niña-dominated
650 periods (here excluding the 2016–2018 period with degraded GRACE signal) showed the opposite pattern, with
651 mass reduction in West Antarctica and to varying degrees, mass increase in East Antarctica. The Amundsen Sea
652 sector typically experiences positive mass anomalies during El Niño-dominated periods and negative anomalies
653 during La Niña-dominated periods.

654 Mass variability in West Antarctica is primarily driven by ENSO-induced ASL pressure anomalies, which
655 modulate the atmospheric circulation and moisture transport. The ASL exhibits high variability in its location,
656 strength, and extent, which influences its impact on the Antarctic Peninsula and West Antarctica. The ASL
657 strengthens and moves closer to the Antarctic coastline during periods when ENSO-SAM are in phase (Hosking
658 et al., 2013), and ENSO has its strongest impact in West Antarctica. In East Antarctica, atmospheric pressure
659 patterns over the Southern Ocean play a crucial role in regulating moisture influx affecting ice mass variability.

660 In summary, this study highlights the complex nature of ENSO teleconnections in modulating AIS mass balance
661 through changes in atmospheric circulation. Rather than exhibiting a simple dipole response, AIS mass variability
662 during ENSO periods is shaped by unique teleconnections and moisture fluxes specific to each period. We
663 acknowledge uncertainties in our analysis due to the relatively short ENSO-dominated periods considered. Some
664 ENSO-related teleconnections may not have fully developed during these intervals, and other processes—such as
665 atmospheric rivers—may have masked or modulated the ENSO signal, complicating the attribution of the
666 observed spatial impacts. Although climate model projections remain uncertain regarding whether future ENSO
667 events will more resemble more an El Niño- or La Niña-like state, they consistently indicate that ENSO will
668 influence Antarctic precipitation patterns. A clearer understanding of ENSO’s role in Antarctic climate is therefore
669 critical for assessing its impact on future SMB and long-term ice mass balance. This requires both process-level
670 understanding and consideration of the net ENSO effect on AIS mass change as explored here.

671 **Code and Data availability**

672 Source code and data will be made available through the University of Tasmania Research Data Portal prior to
673 publication. The GRACE data used is available at <https://gravis.gfz.de/ais>. The ERA5 reanalysis data used in the
674 atmospheric linkage to ice mass variation are publicly available from <https://cds.climate.copernicus.eu/>. The
675 station-derived SAM index from Marshall (2003) are available at <http://www.nerc-bas.ac.uk/icd/gjma/sam.html>.
676 The Niño3.4 index are publicly available from <https://psl.noaa.gov/data/timeseries/month/Nino34/>.
677 RACMO2.4p1 model SMB output can be accessed at <https://zenodo.org/records/14217232> (Van Dalum et al.,
678 2025; Van Dalum et al., 2024).

679 **Author contributions**

680 All authors contributed to the conception and design of the study. JBA performed the statistical analysis and data
681 processing. JBA wrote the manuscript with input from all co-authors. All authors helped with the revision and
682 approved the final version of the manuscript.

683 **Competing interests**

684 The authors declare that they have no conflict of interest.

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