Sustainability of regional Antarctic ice sheets under late-Eocene seasonal atmospheric conditions

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Abstract. The Eocene-Oligocene Transition (EOT) is marked by a sudden δ^{18}O excursion occurring in two distinct phases, approximately 500 ky apart. These phases signal a shift from the warm middle- to late-Eocene greenhouse climate to cooler conditions, with global surface air temperatures decreasing by 3–5 °C and the emergence of the first continent-wide Antarctic Ice Sheet (AIS). While ice-sheet modelling suggests that ice sheet growth can be triggered by declining pCO$_2$, it remains unclear how this transition was initiated, particularly the first growth phase that appears to be related to oceanic and atmospheric cooling rather than ice sheet growth. Recent climate model simulations of the late-Eocene show improved accuracy but depict climatic conditions that are not conducive to the survival of incipient ice sheets throughout the summer season. This study therefore examines whether it is plausible to develop ice sheets of sufficient scale to trigger the feedback mechanisms required to disrupt the atmospheric regime above the Antarctic continent during warm and moist late-Eocene summers and establish more favourable conditions for ice expansion. We aim to assess the sustainability of an incipient AIS under varying radiative, orbital and cryospheric forcing. To do so, we evaluate Community Earth System Model 1.0.5 simulations, using a 38 Ma geo- and topographical reconstruction, considering different radiative and orbital forcings. The climatic conditions prevailing during (and leading up to) the EOT can be characterised as extremely seasonal and monsoon-like, featuring a short yet intense summer period and contrasting cold winters. A narrow convergence zone with moist convection around the region with high sub-cloud equivalent potential temperature exhibits a ring-like structure, advecting moist surface air from the Southern Ocean, both in summer and in winter. This advection leads to high values of moist static energy and subsequent precipitation in coastal regions. Paradoxically, this atmospheric regime — particularly its coastal precipitation in winter — appears to be necessary for the sustenance of the moderately-sized regional ice sheets we imposed on the continent, contrary to our assumption that these ice sheets would disrupt the atmospheric regime. This underscores a hysteresis effect for regional ice sheets on the Antarctic continent, suggesting the potential for a significant volume of ice on the continent without imminent full glaciation prior to the EOT.

1 Introduction

1.1 Eocene-Oligocene Transition and the inception of the Antarctic Ice Sheet

After the pinnacle of extreme warmth during the Early-Eocene Climatic Optimum (EECO; 53–51 Ma) greenhouse world, tem-
peratures globally decreased towards the end of the Eocene (EO) (Anagnostou et al., 2016). The subsequent Eocene-Oligocene
Transition (EOT; 34.44–33.65 Ma) shows a sudden oxygen isotope ($\delta^{18}O$) excursion in deep-sea benthic foraminifera (Hutchin-
son et al., 2021; Premoli Silva and Graham Jenkins, 1993). This excursion occurred in two distinct phases, separated by approx-
imately 500 ky: during the first phase (precursor event; 34.15±0.04 Ma) $\delta^{18}O$ increased with ~0.5‰, indicating a widespread
cooling is evident without large-scale ice build-up (Scher et al., 2011; Katz et al., 2008). During during the second phase
(Earliest Oligocene oxygen Isotope Step (EOIS); 33.65±0.04 Ma) $\delta^{18}O$ increased with ~1.0‰, commonly interpreted as the
occurrence of major glaciation without extensive cooling (Hutchinson et al., 2021). Moreover, the EOT is commonly inter-
preted as the onset of the first continent-wide Antarctic ice sheet (AIS) (Lauretano et al., 2021; Carter et al., 2017; Scher et al.,
2014). This sudden ice sheet growth on Antarctica led the planet to its present-day icehouse state (Pandey et al., 2021) and is —
apart from this $\delta^{18}O$ excursion — commonly implied by: 1. the deposition of ice-rafted debris around the Antarctic continental
margins (Scher et al., 2011; Zachos et al., 1992) and glacial diamictites on the Antarctic Peninsula (Ivany et al., 2006); 2. the
documentation of an extensive sea level rise (fall) in Antarctic coastal (far-field) sediments, collectively indicating large-scale
ice growth on the continent (Stocchi et al., 2013; Katz et al., 2008); and 3. the shift from a chemical to physical weathering
regime on Antarctica (Robert and Kennett, 1997), evident in mineralogical (Passchier et al., 2013) and geochemical (Houben
et al., 2013) changes.

During the lead-up to the EOT two major changes have occurred, both of which have been hypothesised as potential causes
for the onset of Antarctic glaciation. The first involves continental reconfiguration, which led to the opening of both Drake
Passage (DP) between Antarctica and South America and the Tasmanian Gateway (TG) between Antarctica and Australia. The
resulting gateway hypothesis suggests that the opening of these passages led to a comprehensive reorganisation of ocean cur-
rents around Antarctica, the establishment of the Antarctic Circumpolar Current (ACC), and eventual cooling of the Antarctic
region. Although this hypothesis finds support in deep marine proxies (Bijl et al., 2013) and early numerical modelling (e.g.,
Kennett, 1977), it has faced criticism because of three primary reasons: the process of gateway opening occurs over longer
timescales (millions of years) compared to the abrupt onset of the first AIS (Coxall et al., 2005); the timing of the opening
of these gateways is poorly established, and does not seem to align with the timing of the glaciation (Wellner and Anderson,
2013); and modelling studies indicate that the opening of DP and TG has minimal to no impact on the formation of a continental
Antarctic ice sheet (Pollard and DeConto, 2005; DeConto and Pollard, 2003).

(Marine) proxies such as boron isotope measurements (Pearson et al., 2009) and Mg/Ca ratios in benthic foraminifera (Katz
et al., 2008) reveal a downward trend in atmospheric $p\text{CO}_2$ levels throughout the Cenozoic era, decreasing from 1600±200
ppm during the EECO to 850±150 ppm during the EOT (Hönisch et al., 2023). This reduction forms the basis of the second
hypothesis explaining the emergence of the AIS, as lower $p\text{CO}_2$ levels could create favourable conditions for ice growth.
This viewpoint is further substantiated by data derived from terrestrial proxies and pollen analysis from regions proximal to

Antarctica, e.g., by examining bacterial lipids in South Australia (Lauretano et al., 2021) and analysing δD in Patagonian volcanic glass (Colwyn and Hren, 2019). However, this hypothesis is also considered to have limitations, especially because the threshold of model-derived $p\text{CO}_2$ required to trigger glaciation seems to be heavily dependent on the specific model used, often significantly lower than what is indicated by proxy data (Goldner et al., 2014).

60   To reconstruct the growth pattern of the AIS, however, we require proxy data regarding EOT conditions of the Antarctic continent itself. Consequently, other methodologies to investigate landscape formation are crucial, such as seismic reflection (Gulick et al., 2017), radar imagery (Rose et al., 2013; Bo et al., 2009) or digital elevation models (Barr et al., 2022). These methods reveal that ice sheet expansion likely commenced with the emergence of small, high-elevation mountain glaciers within the interior mountain ranges of the continent (Rose et al., 2013; Wilson et al., 2013). These mountain glaciers contributed
65   to the development of larger valley glaciers during a subsequent second phase, which then extended towards the continental margins (Bo et al., 2009), encompassing Sabrina Coast, Prydz Bay and the Weddell Sea (Gulick et al., 2017). The precise timing of these phases, however, remains unclear, and there are recent indications that high-elevation glaciers may have existed well before the EOT due to the occurrence of not only one but multiple EOT precursor events (Barr et al., 2022; Pandey et al., 2021). Subsequently, a period marked by numerous glaciation events persisted until approximately 32.8 Ma, when a stable AIS
70   had definitively formed, encompassing 70–110% of its present-day size and volume (Hutchinson et al., 2021).

1.2   Climate and ice sheet modelling across the EOT

When considering the $p\text{CO}_2$ drawdown hypothesis and the timing of glaciation phases, the question remains regarding the degree to which declining $p\text{CO}_2$ influenced the onset of Antarctic glaciation. In this context, general circulation models (GCMs) are utilised alongside offline ice sheet models (ISMs). In recent years, these GCMs have exhibited a growing ability to sim-
75   ulate snapshot climatic conditions that increasingly align with available proxy data. The primary contribution of these model studies lies in establishing a $p\text{CO}_2$ threshold that functions as tipping point, beyond which continent-wide glaciation becomes inevitable (Tigchelaar et al., 2011). While this threshold has been previously set at 2.7±0.7 PIC (pre-industrial carbon, where 1 PIC comprises 280 ppm $p\text{CO}_2$ and 671 ppb $p\text{CH}_4$) (Gasson et al., 2014; Ladant et al., 2014; DeConto et al., 2008), it appears to be significantly model-dependent and more recent studies struggle to establish a consensus on a universal value (Kennedy-
80   Asser et al., 2020, 2019; Hutchinson et al., 2018). This variability can be attributed — apart from the GCM and/or ISM used — to differences in initial and boundary conditions, primarily concerning the prescribed Antarctic topography and geography along with the resultant atmospheric lapse rate, the absence or presence of an AIS, and $p\text{CO}_2$. Insolation, driven by alterations in orbital parameters, seems to exert a secondary influence by determining the timing of glaciation, specifically in relation to cool(er) Southern Hemisphere summers; however, this effect is contingent upon $p\text{CO}_2$ surpassing the threshold (DeConto
85   et al., 2008). Once continental glaciation takes hold, height-mass balance and ice-albedo feedbacks establish a hysteresis effect, rendering the AIS resistant to warmer climatic periods driven by less favourable orbital parameters (Van Breedam et al., 2022; DeConto and Pollard, 2003).

A limitation of older, low-resolution, model studies lies in their depiction of an unrealistic middle- to late-Eocene climate, falling short in reconstructing its relative warmth. Recent simulations, however, have shown improved accuracy (Lunt et al.,

2021, 2017), attributed to improved model physics (Zhu et al., 2019). Nevertheless, striving to align these late-Eocene simulations more closely with proxy data, a paradox emerges: these simulations depict climatic conditions above the Antarctic continent that are not conducive to the survival of incipient ice sheets throughout the summer season but that reasonably align with available proxies (Baatsen et al., 2024). This study will therefore examine whether — within the constrained potential for limited ice growth in the late-Eocene Antarctic climate — it is plausible to develop ice sheets of sufficient scale to trigger feedback mechanisms required to disrupt the atmospheric regime above the Antarctic continent during the warm late-Eocene and establish more favourable conditions for ice expansion. To do so, we describe the simulations as well as the tools used to analyse both the sustainability of these ice sheets and the atmospheric regime under which they develop in Sect. 2. In Sect. 3 we present the climatic characteristics of the different model scenarios considered and describe the specific consequences of this highly seasonal regime on the sustainability of incipient ice sheets. We discuss our results regarding atmospheric regimes and conditions for sustainability of moderately-sized ice sheets in Sect. 4. Finally, we will present our main conclusions in Sect. 5.

2 Methods

2.1 Model set-up and simulation scenarios

All model simulations were executed using the Community Earth System Model (CESM), version 1.0.5, developed at the American National Center for Atmospheric Research. This GCM comprises four distinct components: Community Atmosphere Model 4 (Neale et al., 2013), configured with a horizontal resolution of $2.5° \times 1.9°$ and encompassing 26 vertical hybrid-sigma levels extending up to 2 hPa; Parallel Ocean Program 2 (Smith et al., 2010), configured with a horizontal resolution of $1.25° \times 0.9°$ and encompassing 60 vertical layers ranging in thickness from 10 m to 250 m; Community Land Model 4 (Lawrence et al., 2011), in which all anthropogenic influences have been eliminated, employed in a static configuration; and Community Ice Code 4 (Hunke et al., 2015), constrained to generate sea ice only when ocean water temperature falls below $-1.8\,°C$.

Three of four model simulations (Table 1) discussed here were conducted by Baatsen et al. (2020), all using 38 Ma boundary conditions: 1. incorporating 4 PIC (4.69 pre-industrial (PI) $p\mathrm{CO_2}$ equivalent) $p\mathrm{CO_2}$ forcing, to simulate the warm middle-Eocene climate (4PIC); 2. incorporating 2 PIC (2.15 PI $p\mathrm{CO_2}$ equivalent) $p\mathrm{CO_2}$ forcing, to replicate a cooling trend towards the EOT during the late-Eocene (2PIC/s); and 3. incorporating 2 PIC $p\mathrm{CO_2}$ levels plus orbital parameters that induce minimal summer insolation at southern high latitudes (2PIC/l), to prompt favourable conditions for ice growth. For more information about specific model parameters and initialisation, see Baatsen et al. (2020). The final 100 yr of each model run are used in this study to generate a representative climatology, distinguishing four different Antarctic regions (Fig. 1). For clarity, greenhouse gas forcings will be indicated as radiative forcing in the text below; insolation forcings will be indicated as orbital forcing.

Moreover, we used 2PIC/s to initialise ice sheet model IMAUICE (Berends et al., 2022), an ISM that employs the shallow-ice approximation (SIA) and incorporates a modified topography from Wilson et al. (2012), projected onto an Antarctic Polar Stereographic grid with a horizontal resolution of 40×40 km. IMAUICE was run until equilibrium was achieved after 30
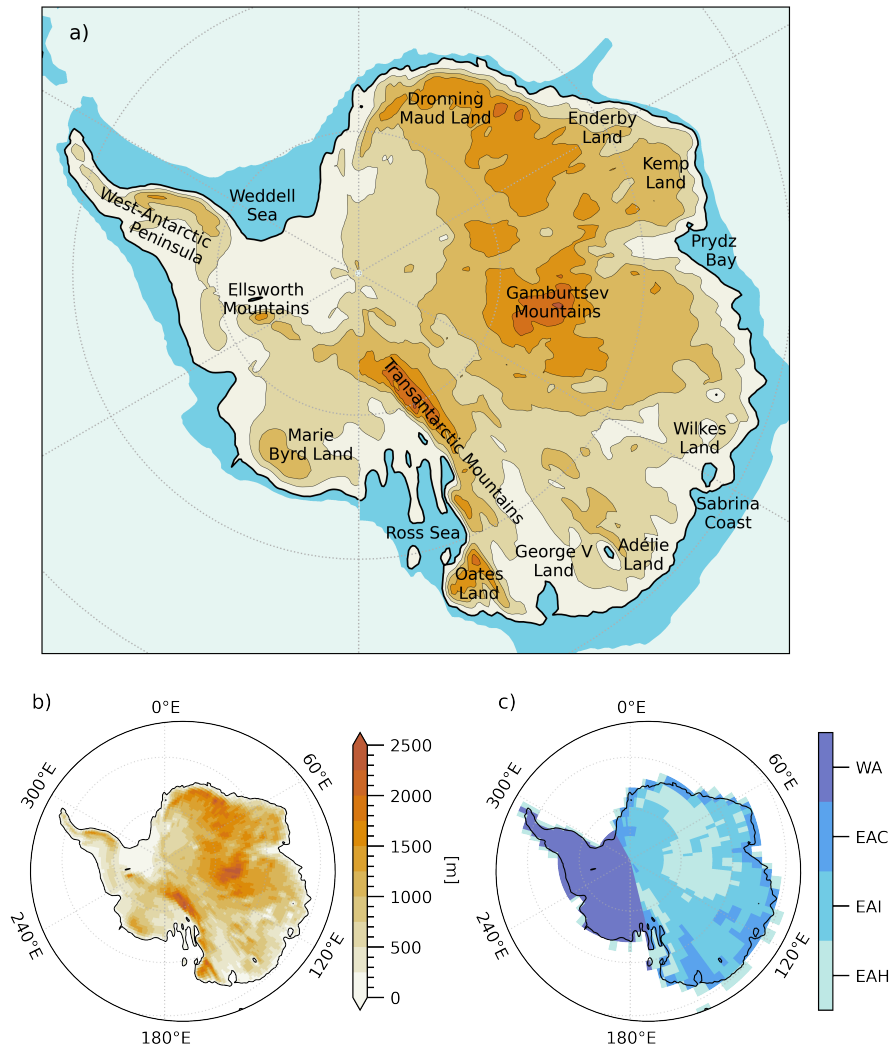
Figure 1. Points of interest is shown in panel a), model topography is shown in panel b) and regional differentiation of the Antarctic continent is shown in panel c). West-Antarctica (WA) includes all area between 166°E and 330°E; East-Antarctica coast (EAC) encompasses all other area below 500 m; East-Antarctica interior (EAI) covers all other area between 500 m and 1300 m; and East-Antarctica highlands (EAH) comprises all area above these elevation values.

ky. The model output was regridded to align with the CESM grid using the GPlates software package (Boyden et al., 2011) and a set of reconstructed plate trajectories (van Hinsbergen et al., 2015; Seton et al., 2012). Surface mass balances (SMBs) were computed using the insolation-temperature method (de Boer et al., 2014). Various ISM simulations were conducted with different lapse rates and orbital, melt, and stress parameters; however, no combination resulted in large-scale ice growth.

Table 1. Model parameters for the four distinct scenarios modelled by Baatsen et al. (2020). e represents eccentricity, ε obliquity, $\tilde{\omega}$ precession and F_s the solar constant.

	4PIC	**2PIC/s**	**2PIC/l**	**2PIC/li**
e [–]	0	0	0.064	0.064
ε [°]	23.44	23.44	22.315	23.315
$\tilde{\omega}$ [°]	n/a	n/a	1.591	1.591
F_s [W m^{-2}]	1361.27	1361.27	1361.27	1361.27
$p\mathrm{CO_2}$ [ppm]	1120	560	560	560
$p\mathrm{CH_4}$ [ppb]	2684	1342	1342	1342

Nevertheless, inducing a cooling of mean summer (DJF) T_s by 5 °C did trigger ice sheet growth (w1m05; Fig. 2), leading to the development of moderately-sized, stable ice sheets in Dronning Maud Land, Oates Land and the West-Antarctic Peninsula.

In an effort to explore the potential for the development of an incipient ice sheet under the most favourable climatic conditions, we initiated for this study an additional CESM simulation to the above-mentioned three, branched off of the end of 2PIC/l. This simulation, 2PIC/li, is conducted over a 400 yr period and incorporates a vegetation/land mask that accounts for land ice (Fig. 2). Since the resulting ice sheets in the IMAUICE simulation are stable in form and the reduction in summer T_s between 2PIC/s and 2PIC/l due to favourable orbital forcing is also ~5 °C, the ice sheet topography in this land mask is based on w1m05. Since our primary interest lies in atmospheric output and the only alteration in 2PIC/li is the sudden imposition of several moderately-sized regional ice sheets, stable outcomes were achieved within a relatively short simulation time of ~75 yr, no spin-up necessary (not shown here). Nevertheless, to avoid any potential complications, we adopted 100 yr climatologies from the interval between 300–400 yr simulation time.

2.2 Atmospheric metrics

We differentiate three variables to compare the atmospheric regime above the Antarctic continent between the different scenarios mentioned above, focusing on the examination of moisture and energetic characteristics of the atmosphere:

$$Q_\mathrm{net} = \mathrm{SW_s} - \mathrm{SW_{ToA}} + \mathrm{LW_s} - \mathrm{LW_{ToA}} + \mathrm{LHF} + \mathrm{SHF} \tag{1}$$

with Q_net [W m^{-2}] being the net radiation balance, cf. Boos and Storelvmo (2016), where SW represent shortwave radiation, LW longwave radiation, LHF latent heat flux, SHF sensible heat flux, s the surface, and ToA the top of the atmosphere.

$$\theta_\mathrm{eb} = T \left(\frac{p_\mathrm{s}}{p_\mathrm{d}} \right)^{\frac{R_\mathrm{d}}{c_\mathrm{d} + c_\mathrm{l}q}} H^{\frac{-qR_\mathrm{v}}{c_\mathrm{d} + c_\mathrm{l}q}} \exp^{\frac{L_\mathrm{v}q}{(c_\mathrm{d} + c_\mathrm{l}q)T}} \tag{2}$$
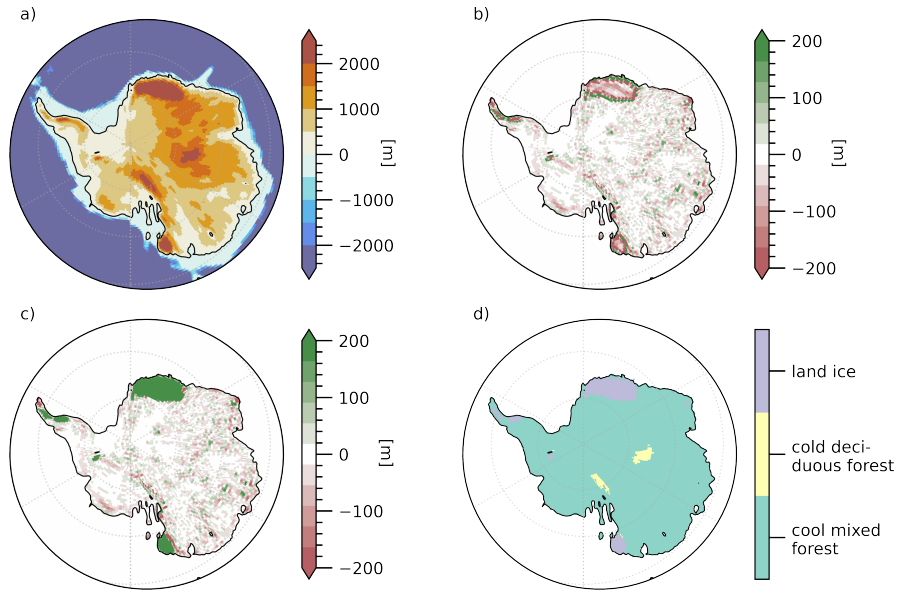
Figure 2. Ice grid transformed into a vegetation mask for input to CESM1.0.5. Panel a) displays Antarctic surface topography with w1m05 ice sheets, smoothed using a 3×3 kernel. Panel b) shows the difference between the effect of the grid smoothing, i.e., the difference between the unsmoothed Antarctic surface topography with w1m05 ice sheets and the smoothed topography. Panel c) illustrates the difference between the original, ice-free, input for 2PIC/l and the smoothed topography. Panel d) depicts the resulting vegetation mask.

145   with θ_{eb} [K] being ~980 hPa sub-cloud equivalent potential temperature, cf. Hurley and Boos (2013), where p_s represents surface pressure and p_d dry air pressure at the level of T, R_d the gas constant for dry air and R_v for water vapour, c_d specific heat at constant pressure for dry air and c_l for liquid water, and H relative and q specific humidity.

$$\text{MSE} = -\frac{1}{g} \int\limits_{p_s}^{200} [c_p T + gz + L_v q] \, dp \tag{3}$$

with MSE being vertically-integrated (from the surface to the tropopause at 200 hPa) moist static energy [GJ m^{-2}], cf. Smyth
150   and Ming (2020) and Hill et al. (2017), where L_v represents latent heat of vaporisation, c_p specific heat at constant pressure for water vapour, and z the air parcel's height.

     Q_{net} aids in analysing the atmosphere's *radiative* state. Employing a convective quasi-equilibrium framework, θ_{eb} offers in turn a simplified depiction of the vertical tropospheric structure as a single near-surface variable. Although this simplification undoubtedly overlooks complexities, it facilitates the analysis of the atmosphere's *convective* state. A similar rationale applies
155   to MSE, which remains conserved during adiabatic ascent, and helps analysing the atmosphere's *energetic* state.

2.3 Ice sheet sustainability

In order to evaluate the potential sustainability of regional ice sheets under 2PIC/li climatic conditions, we use four different methods to calculate surface mass balance (all in units of m yr^{-1}). The first method is based on the surface energy balance, cf. van den Broeke et al. (2011) (SMB$_1$). The three other methods are based on the amount of positive degree days (PDDs). PDDs serve as proxy for the available melt energy on days with a positive T_s (Braithwaite, 1984). Assuming that all annual precipitation falls as snow, this melt can be calculated in different ways: employing a fixed melt rate with PDD calculated as the annual sum of T_s exceeding 0 °C, cf. Heyman et al. (2013) (SMB$_2$); employing a fixed melt rate with PDD calculated using a semi-empirical linear relationship that incorporates a T_s variability term to account for missing information about synoptic variability and the diurnal cycle, cf. Bauer and Ganopolski (2017) (SMB$_3$); and employing the aforementioned semi-empirical linear relationship, but introducing separate melt rates for snow and ice melt (ice melt occurs when all annual precipitation — in the form of snow — is melted away, and the ice sheet base becomes exposed) and considering a refreezing factor for the nocturnal refreezing of snow, cf. Bauer and Ganopolski (2017) (SMB$_4$).

The equations governing these four methods are as follows:

$$\text{SMB}_1 = -\frac{\text{SW}_s + \text{LW}_s + \text{LHF} + \text{SHF}}{c_i} \tag{4}$$

$$\text{SMB}_2 = P_{\text{ann}} - \alpha \Sigma T_s^+ \tag{5}$$

$$\text{SMB}_3 = P_{\text{ann}} - \alpha \text{PDD} \tag{6}$$

$$\text{SMB}_4 = \begin{cases} \alpha_i Q - P_{\text{ann}} & Q < 0 \\ P_{\text{ann}} & Q = 0 \\ \alpha_s (1 - r_s) Q - P_{\text{ann}} & Q > 0 \end{cases} \tag{7}$$

with

$$\text{PDD} = \int_{\Delta t} \left[\frac{\sigma}{\sqrt{2\pi}} \exp^{-\frac{T_s^2}{2\sigma^2}} + \frac{T_s}{2} \, \text{erfc}\left(-\frac{T}{\sqrt{2}\sigma}\right) \right] dt$$

and with

$$Q = \frac{P_{\text{ann}}}{\alpha_s (1 - r_s)} - \frac{\text{PDD}}{\Delta t}$$
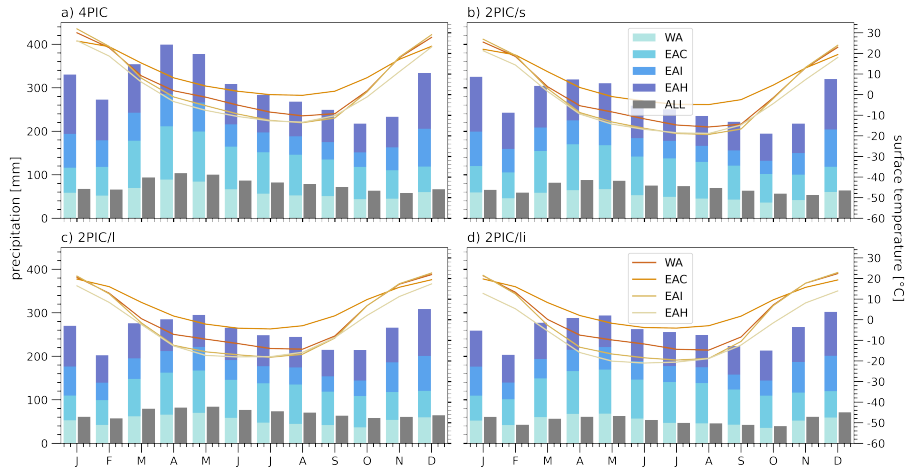
Figure 3. 100 yr climatology for different Antarctic regions. All four EO scenarios are depicted. Lines represent T_s; bars represent monthly P. Different colours indicate the different regions. The grey bars represent continent-averaged (i.e., not summed) monthly P.

where $c_i = 333.55$ kJ kg^{-1} represents the latent heat of fusion of water; $\alpha = 4$ mm °C^{-1} day^{-1} represents a fixed melt rate, and ΣT_s^+ the annual sum of T_s above 0 °C; where $\Delta t = 1$ yr represents the time step, $\sigma = 5$ °C a fixed standard deviation of T_s (representative for present-day ice sheets, cf. Bauer and Ganopolski (2017), and since no specific information is available about empirical relationships for T_s in the Eocene, we apply it in this context as well), and erfc(x) the complementary error function; and where $\alpha_s = 3$ mm °C^{-1} day^{-1} represents the snow melt rate, $\alpha_i = 8$ mm °C^{-1} day^{-1} the ice melt rate, and $r_s = 0.3$ the refreezing factor. Furthermore, SMBs are calculated in such a way that ice melt only occurs over ice sheets, and all SMBs are defined positively for accumulation.

3 Results

3.1 Climatologies

Figure 3 presents a climatology of 2 m surface temperature (T_s) and monthly precipitation (P) for all four model scenarios, distinguishing between the above-mentioned regions. P displays the most variation in 4PIC, with high levels in December and January, followed by a sharp decrease in February, a substantial increase in autumn (MAM) and gradual drying from June to October. This variability is less pronounced in the other three scenarios, although DJ and MAM retain their relatively wet periods. Among the EO scenarios, EAI emerges as the warmest but also driest region; EAC and EAH are the coldest areas, with EAC experiencing significant P in autumn and winter, while EAH is notably wet during summer only. Due to the rapid decrease in T_s between January and February, we define summer for the remainder of this study as DJ (i.e., not DJF).

Figure 4 illustrates JJA- and DJ-mean and JJA-mean and DJ-mean anomalies of T_s, P, 850 hPa wind (u_{850}) and mean sea-level pressure (p_s). Additionally, Table A1 provides the regional mean and spatial standard deviation of these variables.
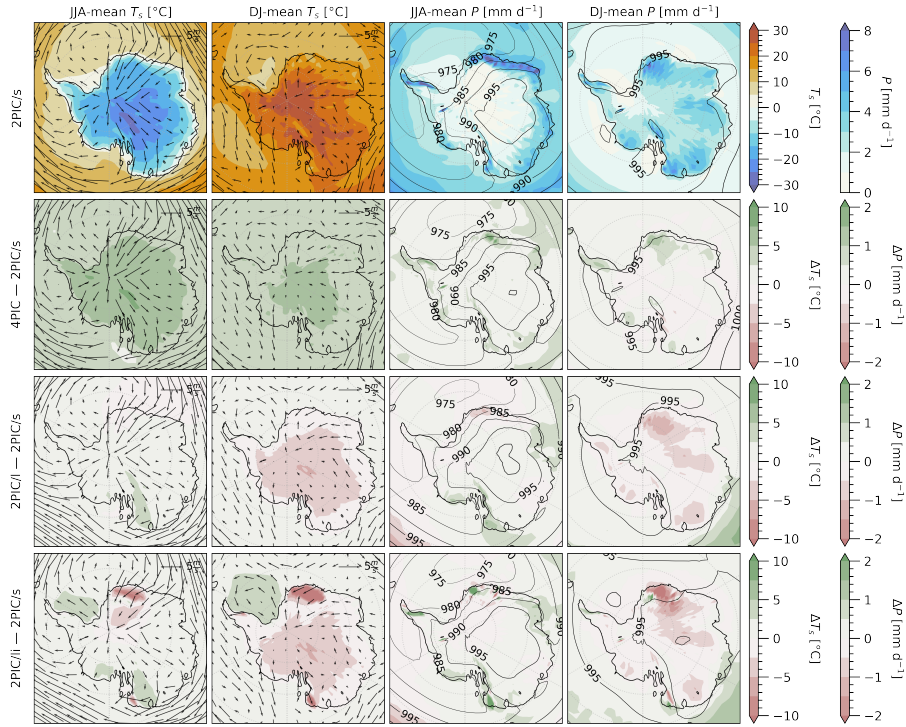
Figure 4. DJ- and JJA-means for 2PIC/s, and DJ- and JJA-mean T_s and P anomalies for the other three scenarios. Maps display T_s (shading in columns 1 and 3), P (shading in columns 2 and 4), u_{850} (vectors in columns 1 and 3) and p_s (contour lines in columns 2 and 4). The anomaly rows for T_s and P show u_{850} and p_s means, rather than anomalies.

Summers are notably warm (reaching up to 35 °C), particularly in EAI, whereas winters are cold (ranging between -15 °C and -20 °C). Among all scenarios, EAC displays the weakest seasonality, characterised by cool summers and mild winters, while EAH shows the most pronounced contrast between the seasons. The seasonal variation in P is also evident. In EAH, summer (~3 mm day^{-1}) is wetter than winter (~1.5 mm day^{-1}). In EAC, particularly along the coastal regions of Dronning Maud Land and the areas more eastward, winters receive substantial precipitation (up to 8 mm day^{-1}). Seasonality slightly decreases when radiative and orbital forcing are reduced.

Apart from the effects of heat and moisture, we observe ascending air above the centre of the continent during summer. This results in weak 10 m winds that move from the 50–100°E sector towards the South Pole, and from the pole either towards ~0°E or the 180–250°E sector (see Fig. 1 for the longitude grid). However, u_{850} remains low (1–2 m s^{-1}) and decreases somewhat when radiative forcing and summer insolation decrease. In winter, the situation is different: a high-pressure area with strongly descending air forms above the Antarctic interior, causing the meridional p_s gradient to intensify. This results in a flow coming from the 0–70°E sector over the South Pole towards the 180–230°E sector. When taking orographic effects into account, this circulation leads to wet conditions on the coast of Dronning Maud Land and the eastern part of the West-Antarctic Peninsula. This circulation pattern persists throughout all four scenarios.
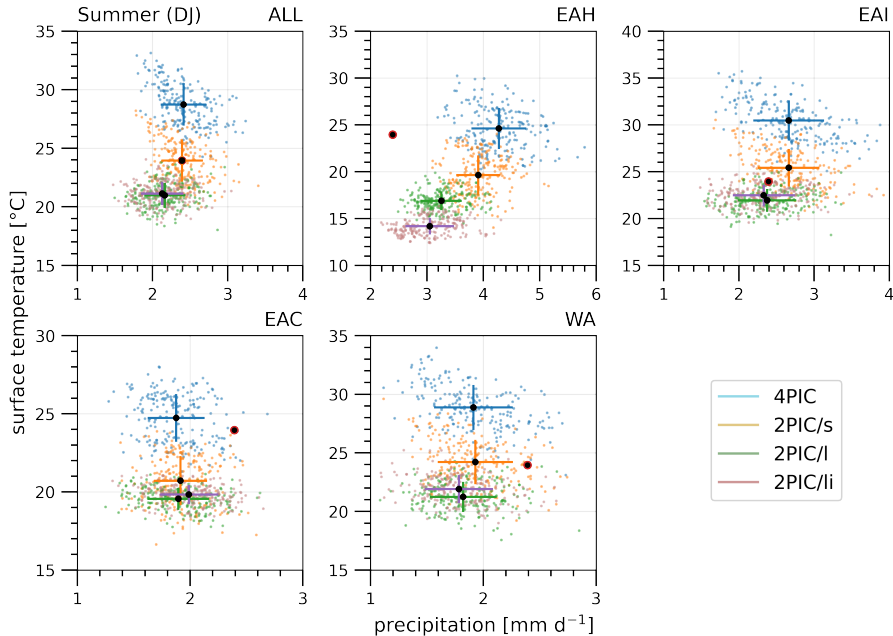
Figure 5. T_s yearly variation plotted against their corresponding P data point, categorised into an Antarctica-wide average and the four regions. The mean is depicted by a black marker, and the coloured lines indicate one (spatial) standard deviation. The x and y axes are not consistent along the panels; therefore a black dot with a red edge is plotted in every panel to mark the 2.5 mm day^{-1} / 25 °C point.

Decreasing radiative and orbital forcing predominantly affects T_s: average P remains relatively stable (~2.2 mm day^{-1}), while T_s undergoes a significant reduction from ~28 °C to ~20 °C (Fig. 5). Only EAH shows a different regime, demonstrating a significant correlation between T_s and P with $r = 0.67$. For ALL, EAI and EAC, correlations are significant but weak, with $r = 0.22$, $r = 0.13$ and $r = -0.15$, respectively; WA does not show any significant correlation. Furthermore, we observe that the imposition of ice sheets only significantly influence T_s and P in EAH (becoming colder and drier, although mainly over the imposed ice sheets themselves), whereas EAI and WA appear to become slightly warmer.

3.2 Atmospheric regime

Heating of the EO Antarctic atmosphere initiates convection and subsequent precipitation, driven by a net radiation surplus. The influence of a low-insolation orbital configuration becomes evident when comparing Q_{net} between 2PIC/s and 2PIC/l, revealing a Q_{net} reduction of ~70% (Fig. 6 and Table A2). Among regions, WA and EAH receive the continent-average amount of summer radiation, while EAI receives more and EAC receives less, in all scenarios. However, there is significant spatial variability within these regions, given the large standard deviation in average Q_{net}. Large amounts of radiation lead to elevated θ_{eb} in all scenarios, but the substantial difference in orbital forcing between 2PIC/s and 2PIC/l does not yield a similar difference for θ_{eb}. EAC consistently exhibits lower θ_{eb} in summer compared to EAH and EAI.
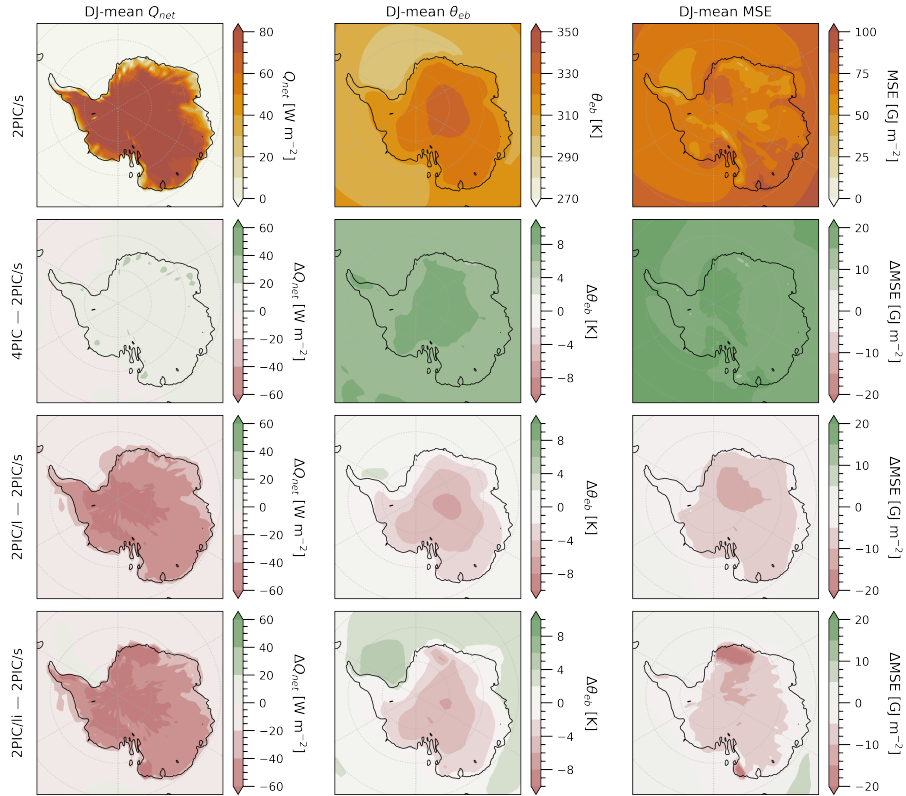
Figure 6. DJ-mean for 2PIC/s, and DJ-mean Q_{net} (left panels), θ_{eb} (middle panels) and MSE (right panels) anomalies for the other three scenarios. The contours have different scales for each variable; however, they are normalised to effectively display the range of possible values.

The attraction of moisture from the surrounding Southern Ocean yields high values for MSE across the southwest of Dronning Maud Land, as well as over Oates and Adélie Land (Fig. 6). Moisture tends to be most abundant in coastal regions and progressively diminishes further inland in EAI and EAH. The topography thus leads to convection of moist air, which inevitably results in precipitation. We discussed P above, revealing the wettest conditions over Dronning Maud, Oates, Adélie and George V Land — all elevated areas relatively close to the Antarctic coast. Especially Dronning Maud Land experiences substantial P during summer. Notably, while Oates and Adélie Land maintain relatively high MSE with decreasing pCO_2 and insolation, even in 2PIC/l, MSE decreases over Dronning Maud Land in 2PIC/l with approximately 30%.

3.3 Effects of imposed ice sheets

The introduction of moderately-sized, regional ice sheets on the Antarctic continent under favourable orbital forcing leads to a slightly drier climate, accompanied by temperatures comparable to those in 2PIC/l (Fig. 3). Throughout the year, p_{s} remains marginally higher in 2PIC/li compared to 2PIC/l. The EAH region displays the most significant reduction in T_{s} and P, due
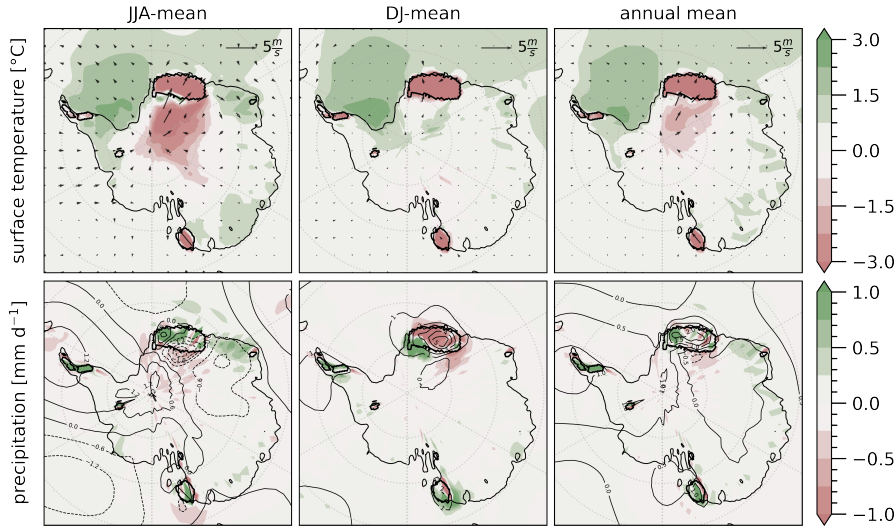
Figure 7. DJ- and JJA-mean anomalies between 2PIC/li and 2PIC/l climatologies. Maps display T_s (upper panels), P (bottom panels), u_{850} (vectors in upper panels) and p_s (contours in bottom panels) anomalies.

to the inclusion of ice sheet areas within its bounds, whereas EAC shows minimal differences (Fig. 4). The continent-wide T_s mean for 2PIC/l and 2PIC/li exhibits nearly equivalent values, whereas the largest standard deviations are observed for $T_\mathrm{s,JJA}$, implying more pronounced regional anomalies during winter than during summer (Table A1).

240   Regions with imposed ice sheets consistently exhibit lower temperatures in both summer and winter (Fig. 7). Over the ice sheet areas, conditions become drier in summer and wetter in winter. Conversely, surrounding areas (situated south of the Dronning Maud Land ice sheet and west of the ice sheets on Oates Land and the Peninsula) experience increased wetness in summer and reduced wetness in winter. Regarding surface temperature, the Weddell Sea and Enderby Land demonstrate higher $T_\mathrm{s,JJA}$, but EAH and EAI experience substantial cooling during winter. The decline in T_s to the south of Dronning Maud Land

245 in winter appears to be linked to a significant shift in wind patterns, marked by a reduced onshore component of the wind. This change is associated with a slight increase in p_s over WA and a slight decrease over EAI and EAC, yielding a weakened airflow across the continent from Dronning Maud Land to Marie Byrd Land. During summer, p_s significantly increases over the Dronning Maud Land ice sheet, along with a slight increase over the rest of the continent.

    The warm and moist atmospheric circulation during Antarctic summer remains largely unchanged when regional ice sheets

250 are imposed (Fig. 8). However, notable regional anomalies emerge over and near the ice sheets. The high albedo of the ice sheets leads to reduced Q_net, resulting in lower θ_eb values within the ice sheet centres. Moreover, the presence of ice sheets leads to decreased moisture content and MSE. A distinct feature is observed in the Weddell Sea area, where higher values of Q_net and θ_eb along with slightly higher MSE levels are noted. Additionally, EAC exhibits slightly higher θ_eb along with increased MSE values. Note also that Q_net slightly decreases over much of the continent, while both θ_eb and MSE seem to

255 slightly increase.
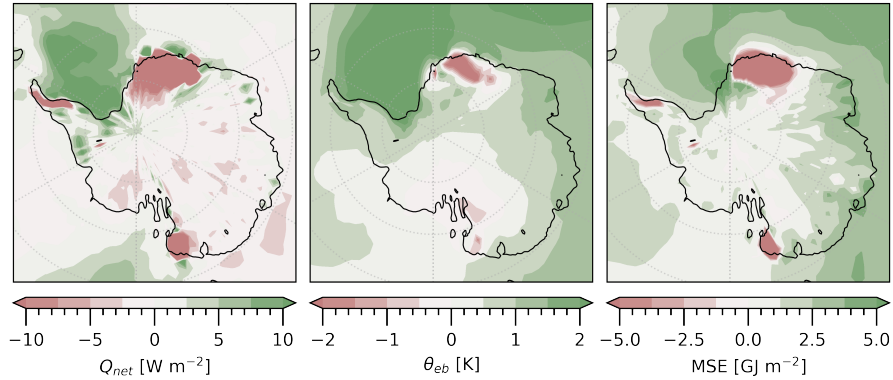
Figure 8. DJ-mean Q_{net}, θ_{eb} and MSE anomalies between 2PIC/li and 2PIC/l. The contours have different scales for each variable, but are normalised to effectively display the range of possible values.

All methods yield a (strongly) positive SMB over the ice sheet areas in 2PIC/li, although SMB2 only shows positive values over the central, higher parts of the ice sheets (Figs. 9, right panels). SMB1 shows less strong positive values, but it covers a larger area where SMB is positive. Incorporating a variability term for T_{s} in calculating PDD (i.e., comparing SMB2 and SMB3) results in a slightly larger area with positive SMB; differentiating between different melt factors for snow and ice (SMB4) yields an even larger area with positivie SMB. This last method also indicates positive SMBs in the high areas of the Transantarctic Mountains and the Gamburtsevs, as well as towards the coastal areas of Enderby and Kemp Land. When comparing SMB1 and SMB4 for the 2PIC/s and 2PIC/l scenarios (Fig. 9, left and middle panels), the same areas for ice sheet expansion become evident — nevertheless, with strongly less positive values for SMB.

4 Discussion

4.1 Climatologies

In the previous section, we described the consistently highly-seasonal climate of the Antarctic late-Eocene under various radiative and orbital forcing scenarios, featuring very warm summers and cold winters. Especially inland seasonality is large, whereas the coastal regions experience milder summers and winters. These areas also receive more winter than summer precipitation, whereas the opposite holds for the higher interior regions. In the latter, we also find higher θ_{eb} values. Moreover, these EO simulations reveal a robust meridional flow that facilitates significant moisture transport towards Antarctica. This flow emerges due to the absence of a weak meridional temperature gradient in summer, and due to a cyclonic polar vortex situated over the Weddell Sea, accompanied by an anticyclone positioned above EAI and EAH, in winter. This seems a crucial part of the Antarctic late-Eocene climate, as the circulation pattern basically redirects the storm track (which is already close to the continent) inland resulting in very high winter precipitation over Dronning Maud Land, but also over West-Antarctica. In
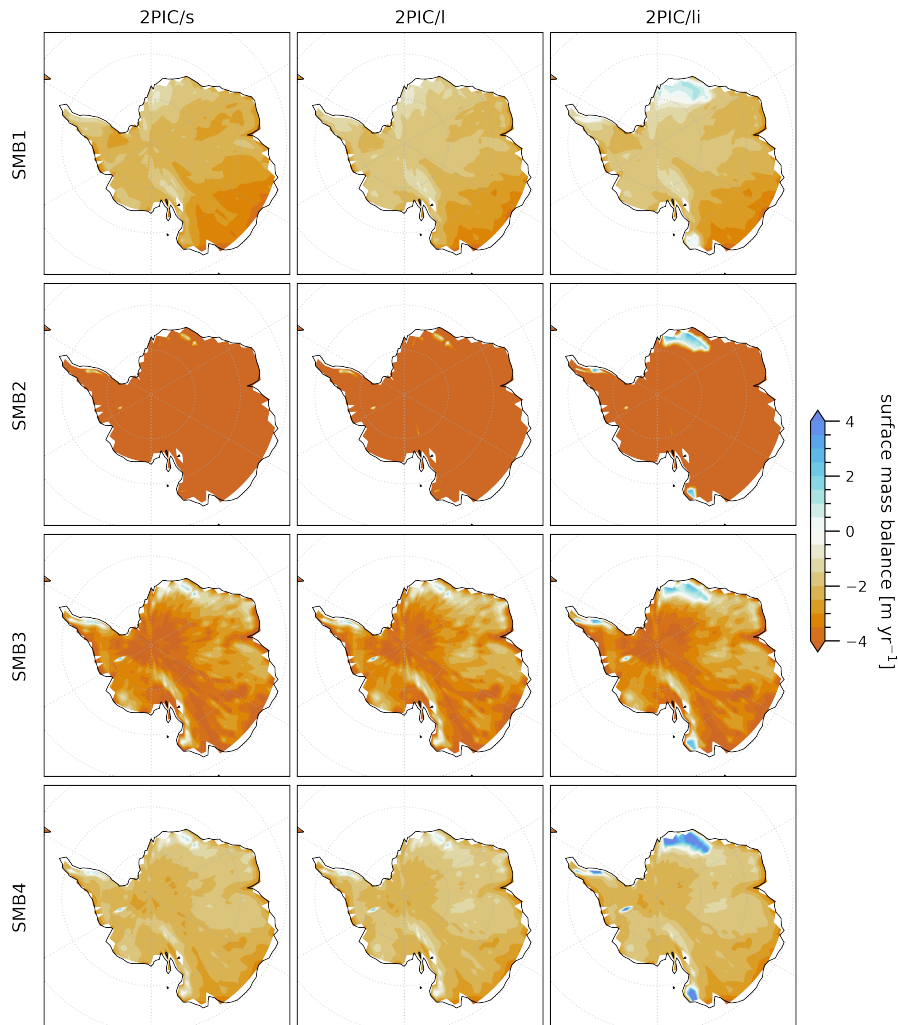
Figure 9. Surface mass balances of imposed regional ice sheets for 2PIC/li (right panels), calculated using four different methods: (1) one based on the surface energy balance (SMB1); (2) a simple PDD method (SMB2); (3) a PDD method including a variability term (SMB3); and (4) a PDD method including a variability term plus using a refreezing factor and separate melt rates for snow and ice (SMB4). All four methods are also used to consider SMBs for 2PIC/s and 2PIC/l (left and middle panels).

275 summer, a persistent cyclone forms, characterised by relatively weaker winds over EAI and EAH. Within this cyclonic system ascending air is observed, providing conducive conditions for the initiation of convection.

Qualitatively, it is reasonable to expect that during JJA a thermal high-pressure area forms over the (East-)Antarctic continent, while a thermal low-pressure area develops over the Weddell Sea — this dipole pattern being a consistent feature across all scenarios. This pattern could, however, be model-dependent, so we have compared the results discussed above with findings

280 from five other GCMs (figures not shown here), evaluated within the context of the Eocene Model Intercomparison Project

(EoMIP; Lunt et al. (2012)) and the Deep-Time Model Intercomparison Project (DeepMIP; Lunt et al. (2021, 2017)). While the time period under investigation in both projects is focused on the EECO (~50 Ma) rather than the late-Eocene, boundary conditions are akin to those employed in this paper (Table A3). We see that CESM1.0.5, the model utilised throughout this study, compares well with other high-resolution models, showing EAI T_s within the range of 25–30 °C, with cooler tempera-
285 tures (15–20 °C) in EAC. Strikingly, CESM1.2 — the successor of CESM1.0.5 — displays a distinct pattern, portraying less warm T_s and cold air over the Gamburtsevs. Regarding p_s, high pressure dominates over the continent in all models, although magnitudes vary across. CESM1.0.5 in the 4PIC scenario is very wet for DJ: only IPSL comes up with a similar P pattern over Dronning Maud Land but its magnitude is smaller than for 4PIC, whereas CCSM3 and HadCM3 show only a moderate signal in EAI. CESM1.2 and NorESM show barely any signal at all. Notably, all models except CCSM3 project relatively moist
290 conditions during summer over Dronning Maud, Wilkes and Oates Land and the Peninsula, but other seasons demonstrate even higher levels of P. Based on this small comparison, we thus conclude that the large seasonality observed in CESM1.0.5 is a robust feature, also evident in other models.

4.2 Atmospheric regime

Very high $Q_{\mathrm{net,DJ}}$ values for 4PIC and 2PIC/s are evident, primarily due to the continuous austral summer sun (Table A2). The
295 influence of orbital parameters is also apparent, with low insolation parameters in 2PIC/l leading to a large reduction in Q_{net}. This surplus of available energy initiates a range of interconnected processes, beginning with an increase in tropospheric T. Relatively high θ_{eb} — especially over EAI and EAH, e.g., centred above the Gamburtsevs — yields unstable air columns. Given that maxima in θ_{eb} align with maxima in upper tropospheric temperature T_u (Nie et al., 2010), we anticipate the occurrence of vigorous moist convection within a (narrow) convergence zone around the θ_{eb} maximum. The remaining region consists
300 of (broad) areas characterised by descending air, thus completing the overturning circulation. Convection is then observed in regions around the edges of a high-pressure system that encompasses the entire interior of the Antarctic continent, characterised by high θ_{eb} (Fig. 6). Likely because this area has a ring-like structure around the pole, surface air is advected from all around the continent (see also DJ-mean u_{850} in Fig. 4). The incoming air, originating from the Southern Ocean, carries moisture, resulting in high MSE in these areas. In order to reach the central part of the continent, air must ascend in almost every region,
305 eventually leading to precipitation. The inflow of maritime air also moderates T_s in these areas, especially when contrasted with the lower-lying interior of the continent that extends through the valley between the Transantarctic Mountains and the Gamburtsevs towards George V Land.

Peak rainfall often coincides with peak surface MSE in monsoonal configurations, due to the fact that cooler and drier air predominantly results in shallow convection (Biasutti et al., 2018). MSE exhibits higher surface values during summer
310 compared to winter, and this pattern is similarly observed for 4PIC in contrast to 2PIC/s and 2PIC/l (Fig. 6). However, this trend is not as clearly visible when considering column-integrated MSE (not shown here). Given that the spatial distribution of MSE is primarily influenced by the spatial arrangement of q_e and that regions characterised by high q_e are regions where precipitation does not rain out significantly, the linkage between MSE and peak rainfall is not evident. Furthermore, very wet regions (Dronning Maud, Oates and George V Land, and the area spanning Prydz Bay to the Gamburtsevs) do not necessarily

correspond to very warm areas, which is likely attributed to the influx of colder air originating from the Southern Ocean. Only the interior of Dronning Maud Land receives over 60% of its annual precipitation during summer, while Oates, Adélie and George V Land, and a narrow coastal strip of Dronning Maud Land also witness significant rainfall during winter.

In these scenarios, we therefore conclude to find a monsoon-like atmospheric regime, albeit at completely different latitudes from where such climates are typically observed today. Our use of various atmospheric metrics broadens this monsoon-like classification compared to the monsoon index recently employed by Baatsen et al. (2024). Additionally, Jacques et al. (2014) identified proxies for significant seasonality in precipitation in EO Antarctica, with summer precipitation rates up to 3 mm day^{-1} and a summer-to-winter precipitation ratio of more than 55%, both comparable to our findings. They attribute the discrepancy between their findings and model outcomes (which generally predict cold and dry conditions) to the underestimation of T_s in model simulations and hypothesise that high- and low-pressure systems alternate more strongly from summer to winter than model simulations suggest. This alternation would result in a seasonal sea-breeze-like circulation, with the advection of moist air towards the continent in summer, and dry, offshore winds in winter. What we add to their findings is a more nuanced view: the inland regions being very dry and cold in winter and moist and very warm in summer, and the EAC region experiencing surface temperatures below freezing in winter, yet with an excessive amount of precipitation due to the constant onshore transport of moist air towards the continent's interior.

4.3 Effects of imposed ice sheets

The height and likely also the size of the imposed regional ice sheets (for reference, the Dronning Maud Land ice sheet in 2PIC/li reaches a maximum elevation of approximately 4.5 km) appear to influence the atmospheric circulation. However, the effects remain regional and do not extend across the entire continent. The interior of the continent, along with the coastal areas of East-Antarctica that are unglaciated, seem to experience little to no influence from the ice sheets on Dronning Maud Land, Oates Land and the Peninsula (Fig. 7). However, areas of EAH and EAI around ice sheets, on average, become slightly colder and drier. In contrast, areas *over* the ice sheets are greatly influenced: they become drier in summer, wetter in winter, and colder year-round. Under these conditions, these ice sheets appear to demonstrate capacity for self-sustenance: despite the still relatively warm summer conditions, SMBs remain nearly to strongly positive across the entire ice sheet area (Fig. 9). Since ice sheets were imposed based on lowered annual surface temperatures, this result is not trivial; importantly, it suggests that there is potential space — particularly in Dronning Maud and Oates Land — for expansion in the surrounding vicinity, which is also evident in Kemp Land and the high regions of the Gamburtsevs and the Transantarctic Mountains.

Other significant changes occur over the Weddell Sea region, where T_s is notably higher during both summer and winter (Fig. 7). During summer, increased incoming Q_{net} contributes to higher T_s, enhanced evaporation and subsequently higher q_e and MSE (Fig. 8). The anti-clockwise, positive pressure anomaly over the Weddell Sea yields air flow from Coats Land encountering the Dronning Maud Land ice sheet, after which air converges and ascends, resulting in positive P anomalies in that area. In winter, the air flow pattern is somewhat similar to the pattern in 2PIC/l, crossing the continent from Dronning Maud Land towards the 180–230°E sector. Although less powerful, air still cools as it moves over and primarily along the Dronning Maud Land ice sheet towards the South Pole and the interior of the continent. The Weddell Sea thus exhibits large positive T_s

anomalies, but its impact on the atmospheric circulation over the continent itself appears to be limited. Nevertheless, a warmer
Weddell Sea could be a potential source for increased precipitation in Dronning Maud Land and the Peninsula, which would
in winter lead to increased snow and ice build-up.

Comparing our model results with available proxies is challenging, as most of these proxies are representative only for
marine environments. Terrestrial proxies from South America and Australia suggest a global T_s decrease of approximately 3–5
°C during the EOT (Colwyn and Hren, 2019; Pound and Salzmann, 2017), while other proxies indicate a smaller T_s decrease
(Lauretano et al., 2021). Methods for subglacial examination of glacial cirques suggest that the AIS likely expanded from high-
elevation mountain ranges or interior massifs toward coastal areas (Rose et al., 2013; Bo et al., 2009), a process that might
have occurred well before the EOT (Barr et al., 2022; Gulick et al., 2017). Furthermore, evidence from Antarctic glaciation,
based on δ^{18}O excursion events, suggests that this glaciation likely occurred within a relatively short time frame of ~500 ky
(Hutchinson et al., 2018). The decrease in T_s indicated by these proxies is comparable to the T_s decrease observed between
the 2PIC/s and 2PIC/l scenarios (Table A1), which suggests that such a cooling trend could be caused by favourable orbital
conditions. The regional ice sheets that could develop in response to this change in orbital forcing are of such a size that they
could sustain themselves; however, these ice sheets do not appear to grow from high interior mountain ranges but seem to
initiate in areas closer to the coast. The Dronning Maud Land ice sheet particularly shows promise for expansion toward the
continent's interior, contrary to the traditional assumption of growing radially outward towards the Southern Ocean.

To assess the influence of the different components of the calculated SMBs, we conducted an additional analysis in which
we set the various contributing elements in Eqs. 4–7 (i.e., SW$_s$, LW$_s$, LHF, SHF, T_s^+, T_s and P_{ann}), one at a time, to zero
(T_s at 0 K, not 0 °C) for 2PIC/li, cf. Gasson et al. (2014) (Fig. 10). When examining SMB1, the sensible heat flux appears
to have minimal impact (only slightly above ice sheet areas, where less heat being absorbed from the atmosphere into the ice
means a positive effect on the SMB), while the latent heat flux exerts a (slightly) negative influence (less evaporation leads to
less energy loss and therefore a negative effect on the SMB). Longwave radiation seems crucial in maintaining the SMB at its
current level, as its absence results in a significantly more negative SMB across all areas. Conversely, shortwave radiation acts
as a constraint on a high SMB, with its absence leading to a marked increase, resulting in a more 'classical' radiation balance.

In the context of SMB2/3/4, the regions where ice sheets have formed in IMAUICE as described in Sect. 2 seem to be
areas where precipitation is the dominant factor. There, SMB becomes less positive in the absence of precipitation, whereas
other parts of the interior seem more sensitive to temperature, as the SMB increases when T_s is set to zero. Some high-
elevated areas also exhibit reduced sensitivity to temperature, suggesting they should be classified within this precipitation
regime. Notably, these effects are most pronounced in SMB4, the most nuanced calculation; in SMB2 and SMB3, EAC is
sensitive to precipitation as well, while EAI and EAH also show sensitivity to temperature. These precipitation-dominated and
temperature-dominated regimes are important in the context of potential formation sites for new ice nuclei: in regions where
we have imposed regional ice sheets, precipitation is sufficient to maintain these ice sheets despite relatively unfavourable
temperatures. Additional sites of interest, where increased precipitation could lead to similar outcomes, then include the high
areas of the Gamburtsevs and the Transantarctic Mountains. An imposed ice sheet in these regions would likely behave similarly
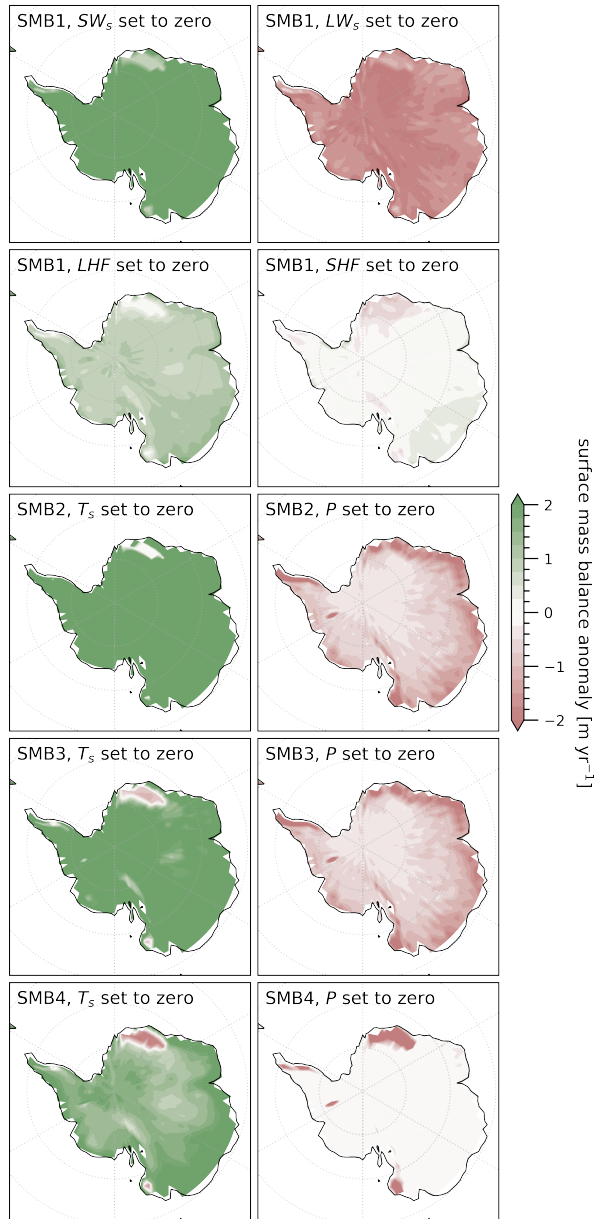
Figure 10. Surface mass balance anomalies for 2PIC/li. For SMB1, we set one component of Eq. 4 to zero for each term in this balance (SW_s, LW_s, LHF, and SHF, respectively). For SMB2, SMB3, and SMB4, we set either the contribution of T or P in Eqs. 5–7 to zero (T_s^+, T_s, and P_{ann}, respectively). Anomalies are shown with positive values showing an SMB increase.

to those we have placed on Dronning Maud Land, Oates Land and the Peninsula, although more precipitation may be necessary for its sustained existence. Ice sheets in other areas would not benefit from this effect and would likely melt away.

385   We observe SMBs in the range of 1–2 m yr^{-1}, potentially enabling the development of substantial ice sheets over a couple of thousands of years. In terms of surface mass balance, a δ^{18}O excursion period of ~500 ky then seems plausible to envision the growth of a continent-wide ice sheet, especially when accounting for positive feedback mechanisms that amplify ice sheet expansion. However, the type of insolation minimum we modelled here is mostly precession-based and therefore only lasts 5–10 ky. SMB would then have to remain substantially high under a much wider range of orbital parameters to yield this

390 long excursion period of 500 ky. The limited climatic differences between the 2PIC/s and 2PIC/l scenario, nonetheless, would suggest that this indeed could be the case.

5   Conclusion

This study presented an analysis of Antarctic climate simulations at 38 Ma, representing the late-Eocene and the EOT, as conducted by Baatsen et al. (2020). The primary focus was to assess the sustainability of an incipient AIS under varying

395 radiative, orbital and cryospheric forcing. The central hypothesis presented above was that an incipient AIS, comprising various regional ice sheets, could induce sufficient changes in the atmospheric circulation to moderate or even disrupt the warm and moist summer climate. With this, we aimed to shed light on the question of how the AIS emerged within a relatively short time frame of around 500 ky, given that during immediately preceding periods summer temperatures on Antarctica could easily reach 30 °C.

400   The climatic conditions prevailing during (the lead-up to) the EOT can be characterised as extremely seasonal, featuring a short yet intense summer period and contrasting cold winters. Precipitation patterns exhibit distinctly regional characteristics, with coastal areas being most wet during winter, while Dronning Maud, Oates, Adélie and George V Land experience largest P during summer. The interannual variability within this climate is limited and aligns with results from other GCM simulations, although it is challenging to make a direct comparison between outcomes due to the distinct boundary conditions utilised across

405 various models. Nonetheless, it is evident that the climatic conditions prevailing at 38 Ma would have been highly inhospitable to ice sheet growth for most of the continent, as limited snow accumulation is expected to survive the summer season.

    This is also reflected in our characterisation of the monsoon-like nature of the atmospheric circulation, which is characterised by a warm, moist, and persistent summer climate driven by continuous incoming solar radiation, as reflected in Q_{net}. Furthermore, we observed a narrow convergence zone with moist convection around the region where θ_{eb} is high. This area

410 exhibits a ring-like structure, with moist surface air being advected from the Southern Ocean, both in summer and in winter. This advection leads to high MSE values and subsequent precipitation in these coastal regions. Paradoxically, this atmospheric regime — particularly its coastal precipitation in winter, under favourable orbital and moderate radiative conditions — appears to be necessary for the sustenance of the moderately-sized regional ice sheets we have imposed on the continent, contrary to our assumption that these ice sheets would disrupt the atmospheric regime over the Antarctic continent. Our findings emphasise

415 a significant hysteresis effect for regional ice sheets on the Antarctic continent, suggesting that these may have been present for a substantial amount of time prior to the EOT, without necessarily implying continent-wide glaciation. Instead, they may

have functioned as a transitional link between the warm and moist climate of the late-Eocene and the onset of full Antarctic glaciation during the EOT.

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Code and data availability. All model output is post-processed using Python 3.12. A selection of the model data used to generate the main figures in this paper and the necessary grids and software code is publicly available on the Utrecht University Yoda platform via https://doi.org/10.24416/UU01-YDFULA. The above data are post-processed to be more accessible and only contain the variables considered in this specific work. The full data from the respective model simulations are available upon reasonable request from the authors.

Author contributions. DV conceived the idea for this study, after which DV, AvdH and MB contributed to the conceptualisation of the narrative and analyses needed. MB and AvdH designed the 4PIC, 2PIC/s and 2PIC/l model simulations; DV and MB designed the 2PIC/li model simulation. DV post-processed the data, conducted the analyses and constructed the figures. DV set up a first draft of the manuscript. MB and AvdH provided revisions to the manuscript, after which DV wrote its final version.

Competing interests. The authors declare that they have no conflict of interest.

Table A1. Annual, DJ- and JJA-mean and (spatial) standard deviation for T_s [°C] and P [mm day^{-1}]. The values are provided for Antarctica as a whole and for EAH, EAI, EAC and WA. Values encompass all four scenarios.

		ALL	EAH	EAI	EAC	WA
4PIC	T_s	5.7±0.5	2.2±0.5	4.9±0.7	10.7±0.3	6.4±0.6
	$T_{s,DJ}$	28.7±1.1	24.6±1.3	30.5±1.4	24.7±10.7	28.9±1.3
	$T_{s,JJA}$	-9.2±1.1	-12.3±1.2	-11.9±1.5	0.4±0.7	-8.0±1.3
	P	2.08±0.10	3.19±0.18	1.91±0.11	2.84±0.13	2.00±0.16
	P_{DJ}	2.41±0.24	4.27±0.34	2.66±0.34	1.87±0.18	1.91±0.28
	P_{JJA}	1.87±0.16	2.82±0.35	1.52±0.16	3.11±0.24	1.91±0.27
2PIC/s	T_s	0.4±0.6	-2.9±0.6	-0.8±0.8	6.4±0.4	1.0±0.6
	$T_{s,DJ}$	23.9±1.0	19.6±1.2	25.4±1.2	20.7±0.8	24.2±1.2
	$T_{s,JJA}$	-15.3±1.2	-18.1±1.4	-18.2±1.7	-4.3±0.8	-14.1±1.2
	P	1.82±0.07	2.79±0.17	1.69±0.09	2.59±0.10	1.71±0.11
	P_{DJ}	2.39±0.21	3.91±0.26	2.66±0.30	1.92±0.16	1.93±0.25
	P_{JJA}	1.59±0.13	2.35±0.31	1.30±0.13	2.84±0.20	1.60±0.24
2PIC/l	T_s	0.5±0.6	-3.1±0.6	-0.8±0.7	6.6±0.4	1.3±0.6
	$T_{s,DJ}$	21.0±0.8	16.9±0.7	21.9±0.8	19.6±0.6	21.2±1.0
	$T_{s,JJA}$	-14.5±1.2	-17.3±1.5	-17.4±1.7	-3.8±0.7	-13.3±1.3
	P	1.80±0.07	2.52±0.15	1.65±0.08	2.56±0.12	1.74±0.11
	P_{DJ}	2.16±0.16	3.25±0.22	2.37±0.24	1.89±0.20	1.82±0.20
	P_{JJA}	1.63±0.15	2.35±0.32	1.35±0.16	2.92±0.24	1.64±0.25
2PIC/li	T_s	0.0±0.5	-5.5±0.5	-1.4±0.6	7.0±0.2	1.3±0.6
	$T_{s,DJ}$	21.1±0.7	14.2±0.6	22.5±0.8	19.8±0.5	21.9±0.9
	$T_{s,JJA}$	-15.4±0.9	-19.4±1.2	-18.9±1.2	-3.3±0.5	13.7±1.2
	P	1.78±0.08	2.43±0.15	1.59±0.08	2.68±0.10	1.74±0.13
	P_{DJ}	2.13±0.18	3.04±0.23	2.33±0.27	1.99±0.19	1.79±0.21
	P_{JJA}	1.60±0.15	2.30±0.30	1.24±0.16	3.00±0.22	1.64±0.26

Table A2. Annual, DJ- and JJA-mean and (spatial) standard deviation for Q_{net} [W m^{-2}], θ_{eb} [K] and MSE [GJ m^{-2}]. The values are provided for Antarctica as a whole and for EAH, EAI, EAC and WA. Values encompass all four scenarios.

		ALL	EAH	EAI	EAC	WA
4PIC	Q_{net}	-79.8 ± 8.9	-77.1 ± 4.2	-79.8 ± 6.1	-73.7 ± 12.7	-82.6 ± 10.3
	$Q_{net,DJ}$	90.4 ± 26.8	90.1 ± 21.4	97.7 ± 15.0	64.6 ± 38.1	89.6 ± 30.4
	$Q_{net,JJA}$	-151.6 ± 18.4	-150.4 ± 5.6	-155.6 ± 3.8	-139.9 ± 29.4	-151.0 ± 25.0
	θ_{eb}	299.8 ± 3.6	304.6 ± 1.2	300.1 ± 2.6	300.0 ± 3.0	297.4 ± 3.3
	$\theta_{eb,DJ}$	331.2 ± 7.2	337.0 ± 4.5	334.8 ± 4.5	324.1 ± 6.7	326.8 ± 6.2
	$\theta_{eb,JJA}$	280.6 ± 5.9	286.4 ± 3.3	279.2 ± 5.7	282.7 ± 6.0	279.2 ± 6.5
	MSE	46.0 ± 6.8	36.8 ± 3.2	45.3 ± 3.3	56.6 ± 5.1	47.6 ± 6.0
	MSE$_{DJ}$	89.8 ± 9.1	78.1 ± 6.8	93.2 ± 6.0	100.0 ± 6.1	87.9 ± 7.9
	MSE$_{JJA}$	23.9 ± 6.0	17.6 ± 2.3	22.2 ± 3.1	32.2 ± 5.9	26.0 ± 6.0
2PIC/s	Q_{net}	-79.4 ± 9.4	-77.0 ± 4.5	-79.6 ± 6.2	-73.5 ± 13.3	-81.8 ± 11.4
	$Q_{net,DJ}$	83.8 ± 28.3	79.7 ± 26.5	91.6 ± 18.3	58.9 ± 38.1	83.8 ± 30.5
	$Q_{net,JJA}$	-147.8 ± 19.1	-147.0 ± 4.8	-151.7 ± 3.5	-136.8 ± 29.6	-146.9 ± 26.5
	θ_{eb}	292.9 ± 3.9	298.0 ± 1.4	293.2 ± 2.9	293.4 ± 3.2	290.3 ± 3.6
	$\theta_{eb,DJ}$	323.1 ± 6.5	328.4 ± 4.1	326.4 ± 3.9	316.9 ± 6.3	318.9 ± 5.7
	$\theta_{eb,JJA}$	274.5 ± 6.2	280.4 ± 3.6	273.0 ± 5.0	276.7 ± 6.2	273.1 ± 6.7
	MSE	34.6 ± 5.5	27.5 ± 2.6	34.1 ± 2.9	43.6 ± 4.7	35.4 ± 4.8
	MSE$_{DJ}$	70.1 ± 7.6	60.6 ± 5.6	72.8 ± 4.5	80.0 ± 5.1	68.2 ± 6.5
	MSE$_{JJA}$	17.1 ± 4.8	12.3 ± 1.8	15.8 ± 2.6	23.9 ± 4.9	18.7 ± 4.7
2PIC/l	Q_{net}	-84.5 ± 9.9	-82.3 ± 4.3	-84.6 ± 6.9	-76.5 ± 14.0	-87.6 ± 11.3
	$Q_{net,DJ}$	26.8 ± 19.3	27.2 ± 17.8	33.0 ± 11.6	10.5 ± 27.9	24.4 ± 20.6
	$Q_{net,JJA}$	-146.9 ± 19.1	-145.6 ± 4.7	-150.4 ± 3.6	-134.6 ± 28.9	-147.0 ± 26.7
	θ_{eb}	292.9 ± 3.7	297.3 ± 1.3	292.9 ± 2.8	293.8 ± 3.3	290.7 ± 3.5
	$\theta_{eb,DJ}$	319.5 ± 4.9	323.7 ± 2.7	322.3 ± 2.7	315.3 ± 4.8	315.9 ± 4.2
	$\theta_{eb,JJA}$	275.1 ± 6.1	281.0 ± 3.3	273.7 ± 4.8	277.4 ± 5.8	273.6 ± 6.7
	MSE	33.1 ± 5.9	25.4 ± 2.5	32.1 ± 3.0	42.2 ± 4.9	34.7 ± 5.1
	MSE$_{DJ}$	62.5 ± 7.4	51.8 ± 4.6	63.8 ± 4.1	74.1 ± 4.6	62.1 ± 5.8
	MSE$_{JJA}$	18.0 ± 4.9	13.0 ± 1.7	16.6 ± 2.5	24.9 ± 4.8	19.7 ± 4.8
2PIC/li	Q_{net}	-84.4 ± 10.2	-85.5 ± 9.4	-84.2 ± 6.3	-77.6 ± 14.6	-86.0 ± 11.7
	$Q_{net,DJ}$	24.5 ± 26.4	16.9 ± 38.5	31.4 ± 17.2	4.9 ± 34.8	25.5 ± 22.1
	$Q_{net,JJA}$	-145.4 ± 19.6	-145.0 ± 7.1	-149.2 ± 3.5	-132.8 ± 29.5	-144.9 ± 27.2
	θ_{eb}	293.1 ± 4.2	297.9 ± 2.2	292.9 ± 3.5	294.6 ± 3.8	290.8 ± 3.9
	$\theta_{eb,DJ}$	320.0 ± 4.8	323.8 ± 3.2	322.8 ± 2.7	315.9 ± 4.7	316.5 ± 4.0
	$\theta_{eb,JJA}$	275.2 ± 7.3	281.8 ± 5.5	273.3 ± 6.1	278.4 ± 7.0	273.6 ± 7.5
	MSE	33.0 ± 6.9	24.2 ± 5.2	32.0 ± 3.9	42.7 ± 6.2	35.0 ± 5.4
	MSE$_{DJ}$	62.8 ± 9.4	49.7 ± 10.5	64.4 ± 5.5	75.0 ± 7.4	62.9 ± 6.1
	MSE$_{JJA}$	17.8 ± 5.6	12.2 ± 2.8	16.0 ± 3.3	25.1 ± 5.9	20.0 ± 5.2

Table A3. Boundary conditions for one model used in EoMIP and for four models used in DeepMIP. Resolution is provided for the atmosphere only, and pCO$_2$ is given in PI concentration (i.e., not equal to PIC).

Model	Resolution	pCO$_2$	Geography
CCSM3	3.75°×3.7°×26	4×	Sewall et al. (2000)
CESM1.2	1.9°×1.9°×30	3×	Herold et al. (2014)
HadCM3	2.5°×3.8°×19	3×	Herold et al. (2014)
IPSL	1.9°×2.5°×39	3×	Herold et al. (2014)
NorESM	2.0°×2.0°×36	4×	Baatsen et al. (2016)

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