Evaluating the Impact of Enhanced Horizontal Resolution over the Antarctic Domain Using a Variable-Resolution Earth Systems Model

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Abstract. Earth System Models are essential tools for understanding the impacts of a warming world, particularly on the

10   contribution of polar ice sheets to sea level change. However, current models lack full coupling of the ice sheets to the ocean, and are typically run at a coarse resolution (1 degree grid spacing or coarser) to save on computational expense. Coarse spatial resolution is particularly a problem over Antarctica, where sub-gridscale orography is well-known to influence precipitation fields. This resolution limitation has been partially addressed by regional climate models (RCMs), which must be forced at their lateral and ocean surface boundaries by (usually coarser) global atmospheric datasets, However, RCMs fail

15   to capture the coupling between the regional domain and the global climate system. Conversely, running high spatial resolution models globally is computationally expensive, and can produce vast amounts of data.

Alternatively, variable-resolution, nested grids are a promising way forward, as they can retain the benefits of high resolution over a specified domain without the computational costs of running at a high resolution globally. Here we evaluate a

20   historical simulation of the Community Earth System Model, version 2, (CESM2) implementing the spectral element (SE) numerical dynamical core with an enhanced-horizontal-resolution (0.25°) grid over the Antarctic Ice Sheet and the surrounding Southern Ocean; the rest of the global domain is on the standard 1° grid. We compare it to a 1° model run of CESM2 using the standard finite-volume dynamical core with identical physics and forcing, including prescribed SSTs and sea ice concentrations from observations. Our evaluation indicates both improvements and degradations in VR-CESM2

25   performance relative to the 1° CESM2. Surface mass balance estimates are slightly higher, but within one standard deviation of the ensemble mean, except for over the Antarctic Peninsula, which is impacted strongly by better-articulated surface topography. Temperature and wind estimates are improved over both the near-surface and aloft, although the overall correction of a cold bias (within the 1° CESM2 runs) has resulted in temperatures which are too high over the interior of the ice sheet. The major degradations include the enhancement of surface melt as well as excessive liquid cloud water over the

30   ocean, with resultant impacts on the radiation balance. Despite these changes, VR-CESM2 is a valuable tool for the analysis of future estimates of precipitation and surface mass balance, and thus constraining estimates of sea level rise.

1 Introduction

The Antarctic Ice Sheet (AIS) contains the largest amount of freshwater on Earth and, with the Greenland Ice sheet, is the greatest potential source of future sea level rise (Pan et al., 2021). Satellite observations have captured net mass loss of the
35 AIS (Shepherd et al., 2019) which has, since 1993, accounted for approximately 10% of observed global mean sea level rise (Oppenheimer et al., 2019). Mass loss follows from a negative difference between the surface mass balance (SMB), consisting of gain by snowfall and loss through sublimation and runoff. and the discharge of solid ice (D) across the grounding line (SMB-D < 0). While SMB over the floating ice shelves that ring the continent does not directly affect sea level rise, surface melt can impact the stability of ice shelves, leading to rapid drainage and hydrofracture (Robel and
40 Banwell, 2019; Banwell et al., 2013) or erosion of the firn layer, which reduces ice shelf resilience to atmospheric warming (Gilbert and Kittel, 2021). The loss of the buttressing effect of ice shelves can induce a speedup in tributary glaciers on the grounded ice sheet, which contributes to sea level rise (Hulbe et al., 2008).

In the current era (since 1979), mass loss over Antarctica has largely resulted from ocean-driven processes, whereby warm ocean waters erode ice shelves from below (Rignot et al., 2019), while mass loss due to meltwater runoff has been negligible
45 (Lenaerts et al., 2019). However, future warming scenarios will be strongly affected by the interplay between mass loss at the margins, potentially enhanced surface melt, e.g. the "Greenlandification of Antarctica" (Trusel et al., 2018) and greater snowfall associated with higher temperatures (Kittel et al., 2021). Other components of the earth system can also affect SMB, including surrounding sea ice, which can impact the intrusion of precipitation (Wang et al., 2020) as well as provide a buttressing effect for tributary glaciers (Wille et al., 2022).

50 Earth Systems Models (ESM) are coupled climate models which capture the interaction between many systems, e.g. ice sheets, atmosphere, oceans and land models. ESMs such as the Community Earth System Model 2 (CESM2) are typically run at coarse horizontal resolutions (e.g. 1°), thus requiring higher-resolution regional climate models (RCMs), forced by coarser reanalysis or ESM outputs at the boundaries, to resolve relatively small-scale physical processes such as orographic precipitation. Variable-resolution(VR) grids combine the advantages of high resolution over focus areas, with coarser
55 resolution elsewhere in the global domain, and therefore avoids the computational costs of running a high-resolution model globally. In contrast to RCMs, a variable-resolution grid can maintain the two-way interaction between the high-resolution domain and the larger global climate system, maintaining an integrated model framework (Huang et al., 2016).

VR-CESM2 employs a spectral element dynamical core (SE; Dennis et al., 2012; Lauritzen et al., 2018) and the version used in this study uses CAM6 physical parameterizations (referred to as physics hereafter). Previous work has demonstrated that
60 VR-CESM captures both the climate of the lower-resolution finite volume (FV) dynamical core while also capturing the high-frequency statistics of higher-resolution models, although biases remain (Gettelman et al., 2019). VR-CESM has also compared favorably to high-resolution regional climate model simulations over California (Rhoades et al 2016; Huang et al., 2016) and the Peruvian Andes (Bambach et al 2021). Finally, surface mass balance and related variables have been evaluated over Greenland, with increasingly higher-resolution VR-CESM runs over an abbreviated period, finding that enhanced

65 resolution produced a positive SMB bias, generally constituting an improvement (van Kampenhout et al., 2019). We note that all of the simulations mentioned thus far have used CAM5 physics, whereas this work over Antarctica as well as a comparison between multiple variable-resolution runs over Greenland (Herrington et al., 2022) are using the newer CAM6 physics.

Within this study, we evaluate a variable-resolution grid over the Antarctic domain, which we refer to as ANTSI (ANTarctic
70 Sea Ice), as it includes both the Antarctic Ice Sheet and larger Southern Ocean domain, with a higher spatial resolution covering the maximum mean extent of sea ice in the historical (1979-2014) era. In addition to the effects of enhanced resolution over the ice sheet, the enhanced spatial resolution over the ocean can alter temperature and moisture fluxes, and strongly impact surface mass balance through the incursion of storms. Thus, the evaluation will focus partially on surface mass balance and energy balance components on the surface, but also the effect of enhanced resolution on the larger
75 Southern Ocean domain. For an evaluation of how the improvements to CAM6 within CESM2 impact surface mass balance and the near-surface climate with the 1° FV dynamical core, we refer the reader to Dunmire et al., 2022. As compared to CESM1 with CAM5 (at the same resolution), CESM2/CAM6 showed improvements in near-surface temperature, windspeed, and surface melt, but excessive precipitation (Dunmire et al., 2022).

Here we will focus specifically on the combined impact of enhanced resolution and SE dynamical core over the Antarctic
80 domain. We will compare these results to similar model runs with identical physics and forcing, but with a lower resolution and using the FV dynamical core. Model outputs will be compared between these model runs as well as to reanalysis, in-situ weather station data and regional climate models.

Data and Methods are described in Section 2, Results in Section 3 (including surface mass balance in Section 3.1, followed by drivers of enhanced moisture in Section 3.2 and finally impacts on the radiation balance in Section3.4), and Discussion
85 and Conclusions in Section 4.

2 Data and Methods

2.1 Model: CESM2

The ESM used here, the Community Earth Systems Model 2.2 (CESM2.2; Herrington et al., 2022; Danabasoglu et al., 2020) couples several climate components, including the atmosphere (Community Atmosphere Model (CAM; Neale et al., 2010),
90 ocean (by the Parallel Ocean Program (POP2; Smith et al., 2010)) and sea ice (the Community Ice CodE for sea ice (CICE; Hunke & Lipscomb, 2010)), land (The Community Land Model (CLM; Lawrence et al., 2011)), and ice sheets (Community Ice Sheet Model (CISM; Lipscomb et al., 2013)). Currently, CISM is only active for the Greenland Ice Sheet, with the coupling for the AIS in development.

CAM6 physics in CESM2 is described in detail in Gettelman et al 2019. The SE VR configuration is described in Herrington
95 et al. (2022).

2.1.1 The ANTSI grid

The ANTSI (ANTarctic Sea Ice) grid (Fig. 1a) is implemented in CESM2.2, with 32 atmospheric layers. The interior domain has a resolution of 0.25°, while nominal 1° (standard) grid in the exterior, with intermediate-resolution points along the boundaries, which extend as far north as 55°. These simulations use the AMIP setup (atmospheric model intercomparison project; Gates et al., 2019), which is a protocol where land and atmosphere components are freely evolving, but use prescribed sea-surface temperatures (ERSSTv5 – Huang et al., 2017) and sea-ice (HadISST- Rayner et al., 2003), in this case for the period 1979 to 2014.

In addition to standard monthly outputs, we produce daily outputs for selected variables for the surface and 3-hourly outputs for selected variables for both the atmosphere and ice sheet surface. These higher-temporal resolution outputs will be used for future analysis of atmospheric rivers and forcing of firn models in future work. The computational cost is approximately 23,000 core hours / model year, and the enhanced storage requirements will scale with the number of cells. For example, the standard 1° FV grid has 55296 cells, whereas the ANTSI grid contains 117398 gridcells (thus requiring ~double storage of a 1° model)

Elevation over Antarctica (Fig. 1b) is highest in the interior, and highly variable at the margins, and ANTSI captures finer resolution than the 1° FV grid over both the ocean and ice sheet. Thus, the enhanced resolution of ANTSI better captures topography along the coasts, with some regions of the grounded ice sheet resolving over 400m higher at the ice sheet margin (e.g. the spine of the Antarctic Peninsula) while ice shelves show slightly lower elevations (Fig. 1b,d).

[Figure 1]

2.1.2 CESM2 AMIP (GOGA) – Used for evaluation

This evaluation primarily focuses on a comparison with the CESM2 CMIP6 AMIP simulation output (Danabasoglu et al 2019), which are identical to the variable-resolution ANTSI runs presented here, except for the grid spacing and the dynamical dycore. The CESM2 CMIP6 AMIP ensemble contains 10 members, all using the nominal 1° resolution with 32 atmospheric levels, with observationally-based global sea-surface temperatures identical to the forcing for the ANTSI grid.

Surface mass balance (SMB, in gigatons, or GT yr-1) is calculated for both AMIP and ANTSI as follows (adapted from Lenaerts et al., 2019):

$$SMB = Precipitation - Runoff - Sublimation/Evaporation \qquad (1)$$

$$Precipitation = Snow + Rain \qquad (2)$$

$$Runoff = Melt + Rainfall + Condensation - Refreezing - Retention \qquad (3)$$

For integrated surface mass balance elements as well as snowmelt comparisons, we remap from the finer resolution to the coarser-resolution grid using the Earth Systems Modeling Framework (ESMF), described at http://earthsystemmodeling.org/,
130 using their first-order conservative method and accounting for the percentage of the gridcell that is covered by glacier.
For all other comparisons, in order to preserve the spatial characteristics of the finer resolution, we regrid from a lower resolution to the finer ANTSI resolution using the ESMF bilinear method.

2.2 Datasets Used for Evaluation

135 We compare surface mass balance values to those from RACMO2.3_p2 (van Wessem et al., 2018), RACMO2 hereafter. RACMO2 is a hydrostatic regional climate model (RCM) forced at the boundaries with ERA-Interim, with a multi-layer snow scheme (Ettema et al., 2010), a drifting snow across the ice sheet (Lenaerts et al., 2010, 2012), a sophisticated albedo scheme (Kuipers Munneke et al., 2011) and orography derived from Bamber et al. (2009).

140 Monthly-averaged ERA5 (Hersbach et al., 2020) data is used here for the 1979-2014 period for near-surface temperature, wind and energy balance components as well as temperature, geopotential height, moisture and wind profiles over the Southern Ocean. This dataset assimilates observations into a numerical weather prediction model, producing data at an hourly resolution from 1950 to the present, a horizontal resolution of 31km, 139 vertical levels (to 1 Pa) and an assimilation of several data products for an elevation (ECMWF, 2016).
145 For temperature, we note that ERA5 has been shown to exhibit a slight cold bias in winter (excepting the Antarctic Peninsula) and a warm bias in summer (excepting West Antarctica) (Zhu et al., 2021).

Automatic weather station (AWS) observations are used here for near-surface temperature alone (as wind speed differences were shown to be negligible), retrieved from a collection of 133 automatic AWSs previously evaluated over the AIS
150 (Gossart et al., 2019). These were limited to stations where greater than 10 years of near-surface temperatures were available and where elevation differences between the station and the resolved elevation (from either AMIP or ANTSI) were smaller than 100 m. Additionally, we apply a temperature adjustment to the AMIP or ANTSI elevation for each AWS using a temperature lapse rate of 6.8°C/km (Martin and Peel, 1978). This final set is divided into bins for elevation, with 21 stations > 500m, one station between 500 and 1000 m above sea level (a.s.l.), 3 stations between 1000 and 2000 m, 8 stations
155 between 2000 and 3000 m and 4 stations above 3000 m.

For comparisons to melt observations, we use melt fluxes calculated empirically from radar backscatter from the QuikSCAT (QSCAT) satellite (Trusel et al., 2013), available at 27.2 km2. For comparisons to surface mass balance, we use the AIS SMB reconstruction from Medley and Thomas (2019), which interpolates ice core SMB records using atmospheric
160 reanalysis.

3 Results

3.1 Datasets Used for Evaluation

3.1.1 Integrated Values for Surface Mass Balance

165 SMB is lowest in the high elevations of the AIS desert interior, where storms rarely penetrate, and much higher at the coastal margins (Mottram et al., 2021). ANTSI annual mean (1979-2014) AIS integrated SMB is 2668 GT yr^{-1}, with a temporal standard deviation of 123 GT yr^{-1}, as compared to the AMIP SMB mean over the same period of 2515 GT yr^{-1}, with an ensemble standard deviation of 53 GT yr^{-1}. This places integrated ANTSI SMB values within one standard deviation of the AMIP SMB mean. Regions here (Fig. 1d) are divided by land cover (grounded, ice shelf, combined) and are calculated using

170 basins described in Zwally et al. (2002), with all SMB values and trends listed in Table 1. Mean integrated ANTSI SMB values are slightly higher, but within one standard deviation of, the AMIP ensemble mean, for East Antarctica and West Antarctica, but not for Antarctic Peninsula (151 ± 13 GT yr^{-1} for ANTSI vs 113±6 GT yr^{-1} for AMIP), which is driven by enhanced SMB over the grounded ice sheet (106 ± 10 GT yr^{-1} for ANTSI vs 72±4 GT yr^{-1} for AMIP).

175 [Table 1]

Regionally integrated SMB from ANTSI over the 1979-2014 period is provided in Figure 2. The figure shows several statistically significant (p < 0.05) trends, including a -0.80 GT yr^{-2} negative trend in SMB over East Antarctic ice shelves which is not replicated by AMIP (Fig. 3b), as well as an positive trend over the grounded ice sheet of the AP for both AMIP

180 (0.24 GT yr^{-2}) and ANTSI (0.51 GT yr^{-2}) .

3.1.2 Spatial Patterns for Surface Mass Balance

The spatial pattern of SMB differences between the higher-resolution ANTSI and the coarser-resolution AMIP (Fig. 3b) results from the interaction between the general atmospheric circulation and elevation differences resulting from enhanced spatial resolution (Fig. 1b). This results in lower SMB values in ANTSI (as compared to AMIP) towards the Ronne and Ross

185 ice shelves and greater SMB values in the high interior. In particular, we note differences over the Antarctic Peninsula ("AP" in Fig. 3b), where SMB values are higher to the west and lower to the east, and West Antarctica ("WA" in Fig. 3b) where differences occur in regions strongly affected by orographic precipitation (discussed in Results).

[Figure 3]

190 To contextualize ANTSI AIS SMB results, we compare SMB results to those calculated from RACMO2 as well as the SMB reconstruction. (Fig. 3c,d)). Grounded AIS integrated SMB values for both AMIP and ANTSI are substantially higher than either RACMO2, at 1997 ± 92 GT yr^{-1} or the reconstruction, at 1953 ±322 GT yr^{-1}, though there is substantial spatial variability in the differences. Over West Antarctica (denoted "WA" in Fig. 3b), both comparisons show similar bias patterns, whereby regions where ANTSI SMB estimates are lower show better agreement with the reference dataset, and where

195 ANTSI SMB is higher, the bias is worse. As compared with RACMO2 results (where SMB values are available over ice shelves), results are mixed, with the Ronne, Amery and Larsen C ice shelves showing better agreement in ANTSI, but several other ice shelves (including the Ross ice shelf) showing better overall agreement with AMIP. Notably, over the Antarctic Peninsula, northern regions near the Larsen C ice shelf typically show better agreement with ANTSI results. While large regions on Dronning Maud Land ("DM" 30°W to 60°W) towards the interior show a consistently lower bias in the

200 coarser-resolution AMIP, other regions of East Antarctica show inconsistent bias increase/reduction between the two reference datasets.

3.1.3 Surface Mass Balance component: Surface melt

Mean spatially-integrated surface melt values in ANTSI are similar to AMIP over both the Antarctic Peninsula and West
205 Antarctica (i.e. the ANTSI mean ± one standard deviation of the temporal mean overlaps with the AMIP mean ± one standard deviation of the ensemble mean). Mean spatially-integrated values for regions are shown in Supplemental Table 1 and temporal plots for spatially-integrated values are shown in Supplemental Fig. 2.

Over East Antarctica, values are significantly higher over ice shelves (ANTSI: 59 ±20 GT yr-1, AMIP: 30±4 GT yr-1), as well as the grounded ice sheet (ANTSI: 34 ±11 GT yr-1, AMIP: 11±2 GT yr-1). Trend analysis (where only significant

210 trends, i.e. p < 0.05 are considered), indicates a weak positive trend in AMIP over East Antarctica (0.14 GT yr-2 over ice shelves, 0.07GT yr-2 over the grounded ice sheet) and a weak negative trend over the grounded ice sheet of West Antarctica (-0.09 GT yr-2). ANTSI shows a stronger positive trend over the ice shelves of the Antarctic Peninsula (0.26 GT yr-2). In summary, surface melt is intensified within ANTSI in some, but not all, ice shelves. These conflicting biases (despite all ice shelves being resolved to lower elevations in ANTSI) suggest that changes in surface melt are a product of both increased

215 near-surface temperature as well as changes in atmospheric circulation (both of which can result from enhanced resolution). As compared to AMIP values, mean surface melt in ANTSI is enhanced over the Antarctic Peninsula on the western side, but reduced over the eastern side, including the Larsen C ice shelf; this is a direct impact of reduced westerly flow over the AP (discussed further in a later section focused on wind) resulting from the better resolved topographic barrier. Surface melt is enhanced over much of East Antarctica (Fig. 4a,b) and West Antarctica (Fig 4c,d) as well, including the Getz, Brunt

220 Amery and Shackleton ice shelves (Fig. 5a). However, we note that over Amery and Shackleton ice shelves, this represents a correction of a negative bias within AMIP, while over most other ice shelves this represents an enhanced positive bias (Fig. 5b).

[Figure 4]

225   [Figure 5]

3.2 SMB Components: Precipitation

Precipitation is the dominant component of SMB over the AIS, and we find that spatial patterns of enhanced/reduced SMB (Fig. 3b) are driven by differences in large-scale precipitation, especially in winter (Fig. 6a), with the summer precipitation contribution to the surplus at higher elevations being smaller than those in winter (Fig. 6c) Over the larger Southern Ocean

230   domain, precipitation is higher in ANTSI than in AMIP (potentially due to the smaller time-step in ANTSI), with the exception of the southern Weddell Sea, where the substantially better-resolved (higher) Antarctic Peninsula mountain range in ANTSI inhibits westerly flow and enhances the orographic precipitation gradient between its windward and leeward side. In addition, this enhanced precipitation is partially driven by enhanced meridional vapor transport towards the Weddell Sea sector and much of East Antarctica, especially in winter (Fig. 6b) followed by redistribution driven by enhanced zonal vapor

235   transport in winter (a result of enhanced zonal windspeeds in ANTSI), noting that zonal vapor transport over the ocean is reduced in ANTSI overall (Supplemental Fig. 3). The atmospheric changes producing this enhanced poleward flow are discussed further in Section 3.3.

[Figure 6]

240   Enhancing resolution resulted in substantial changes to total cloud water path (TCWP, both liquid and ice). TCWP values aggregated by latitude are greater in ANTSI (as compared to AMIP) in winter, while in summer, ANTSI values are lower within the 75°S to 68°S latitude range. This net effect is a combination of changes in both the liquid and ice components, with the biases offsetting each other within the interior of Antarctica during summer. Total liquid cloud water path (TLCWP) is higher in ANTSI vs AMIP over the larger ocean domain during all seasons (Fig. 7c,d) and over the AIS

245   during winter (Fig. 7c). As lower-resolution AMIP values already showed a high bias compared to ERA5, this represents a further-enhanced bias in ANTSI. However, TLCWP values are smaller in ANTSI over the interior grounded ice sheet during summer (Fig 6b) and this represents an improvement compared to ERA5 (Supplemental Fig. 4). Total cloud ice water path (TCIWP) is enhanced by increasing spatial resolution in all seasons, over the ice sheet as well as the interior. As AMIP simulations had a low bias compared to ERA5 estimates (Supplemental Figure 3c,i), this amounts to an improvement in bias

250   over the summer (Fig. 7f), a reversal to a high bias over the interior ice sheet and lower-latitude Southern Ocean, and an improvement over the ocean immediately surrounding the AIS (Fig. 7e).

These results reflect similar spatial patterns in Greenland showing enhanced orographic precipitation in the Southeast and drying in the North (van Kampenhout et al., 2018) and we compare these to recent findings in the Discussion section (4).

255   [Figure 7]

3.3 Drivers of Enhanced Moisture Advection

The convergence of precipitation over the AIS is potentially a product of both moisture evaporated over the ocean and
260 changes in winds that pull this moisture poleward. Cloud properties can be affected by the enhanced moisture in the
atmosphere. As the Clausius-Clapeyron relationship specifies that water-holding capacity of air (saturation vapor pressure)
increases 7% with every 1°C of warming (Held and Soden, 2006), even a small change in temperature can strongly affect
moisture in the atmosphere and, potentially, cloud cover (though the latter is a product of the specific microphysical
scheme). In this section, we discuss changes in temperature and wind structure, for both winter and summer, at the surface
265 and aloft, as potential drivers for enhanced moisture advection towards the AIS.

3.3.1 Temperature

Overall, temperatures in ANTSI are higher than AMIP both at the surface and at higher levels in the atmosphere. Biases over
the ice sheet are higher over the ice sheet than over the ocean, with the strongest biases shown during winter. Where biases
are positive during winter over the ice sheet (the majority of the ice sheet), ANTSI biases are 1.76±1.26°C warmer than
270 ERA5 and 2.62±1.27°C warmer than AMIP. Biases over the ice sheet during summer are positive over most of the ice sheet
and slightly reduced in comparison to winter biases, averaging 1.59±1.13°C as compared to ERA5 and 1.11±0.68°C as
compared to AMIP. (Supplemental Table 2). Temperature biases at 500 hPa are substantially reduced overall (Supplemental
Table 3).

Although temperatures are warmer overall, several regions are cooler, i.e. over the ocean at lower latitudes and to
275 the east of the Antarctic Peninsula, including the Weddell Sea region (Fig. 8a,c). This pattern is likely driven by the
enhanced blocking of the AP, which likely produce precipitation differences shown in Fig. 6a. As compared to ERA5 values
in summer, the warmer atmosphere in ANTSI (Fig. 8b) reduces a cold bias present in AMIP (Supplemental Fig. 6o), over the
interior East Antarctic Ice Sheet and the ocean surrounding the AIS. However a warm bias in AMIP is slightly enhanced in
ANTSI over the West Antarctic Ice Sheet and the regions of the East Antarctic Ice sheet nearest to it. Higher winter
280 temperatures in ANTSI reduce a strong cool bias in AMIP (Supplemental Fig. 5o) as compared to ERA5 over both the ocean
and ice sheet, even reversing signs to show a warm bias in portions of the East Antarctic Interior (Fig. 8d).
[Figure 8]

We also examine temperature biases as compared to AWS stations divided by season and elevation bins (Fig 9a-d),
finding (a) a reduced positive temperature bias in ANTSI compared to larger positive biases in AMIP at elevations < 500m,
285 but (b) a warm bias that intensifies with increasing elevation. This results in the partial correction of a cold bias at high
elevation during the summer in ANTSI relative to AMIP (Fig. 9). In the winter and shoulder seasons within some higher-
elevation areas, the bias changes in sign, from a cold bias in AMIP to a warm bias in ANTSI. We note that within shoulder

seasons and winter, the warm bias in the > 3000m elevation is enhanced substantially in SON and JJA. AWS comparisons therefore demonstrate increasing biases with increasing elevation similar to patterns shown in the comparison with ERA5.

290   [Figure 9]

The warming produced by enhanced resolution is also shown at lower pressure levels, higher in the atmosphere. Comparisons of temperatures at 500 hPa in both summer (Supplemental Fig. 6p-r) and winter (Supplemental Fig. 5p-r) show enhanced warming over the entire domain, largely eliminating a cold bias in AMIP (compared to ERA5) over the AIS.

Previous work has discussed how this increase in temperature could be produced, namely by enhanced horizontal
295   spatial resolution enhancing vertical velocities, thus generating greater condensational heating in CLUBB macrophysics within CAM (Herrington and Reed, 2020). Overall, we consider the temperature changes produced by enhanced resolution to be an improvement.

3.3.2 Wind

The near-surface wind climate in Antarctica is governed by higher-speed katabatic winds and a large-scale pressure gradient
300   force (PGF), both of which are stronger in winter, (van den Broeke and van Lipzig, 2003).

Seasonal differences in mean winter wind speed between AMIP vs ANTSI show enhanced wind speeds in ANTSI where higher elevations are resolved and lower wind speeds on the lee side of topography (e.g. the East Antarctic Peninsula). Generally, negative AMIP biases are improved , but not eliminated, in ANTSI in the interior as well as in the escarpment region, especially in winter (Fig. 10a,b). Where near-surface winter windspeed biases are positive (in comparison to the
305   reference) over the ice sheet, mean ANTSI windspeeds are 1.00 ±1.13 m/s higher than ERA5 and 0.53 ± 0.55 m/s higher than AMIP. All other mean biases over the ocean in winter or in summer for either the ocean or ice sheet differ by less than 0.8 m/s (Supplemental Table 3). We note that ANTSI near-surface wind speeds at higher elevations in East Antarctica are higher than AMIP (Fig. 10a), but lower than ERA5 (Fig. 10b).

To better understand factors contributing to the strong convergence of water vapor over the region, we show a comparison
310   between the meridional and zonal components at 500 hPa, finding that zonal wind speeds are reduced over the ocean, but enhanced in the interior (Fig. 10c) and that meridional wind speeds are higher from the ocean towards the center of East Antarctica. For near-surface as well as meridional and zonal wind speeds at 500 hPa, this represents an overall improvement as compared to AMIP simulations (Supplemental Fig. 5). These improvements are consistent (though less pronounced) in the summer season as well (Supplemental. Fig. 6).

315   [Figure 10]

In the aggregate, we find that both temperature and wind fields are improved by enhanced resolution, with the exception of excessive warming in the high interior during winter.

3.4 The Surface Energy Budget

320   The energy available at the surface for melt is described below:

$$QM = SW_{net} + LW_{net} + QH + QE + QR + GR \qquad\qquad\qquad (4)$$

Here, SW_{net} is net shortwave radiation ($SW_{net} = SW_{down} - SW_{up}$), LW_{net} is net longwave radiation,($LW_{down} - LW_{up}$), QH =
325   sensible heat transfer, QE = latent heat transfer, QR = energy supplied by rain, and GR is = energy supplied by ground flux.
We have ignored QE, QR and GR for the purposes of this study, as we expect rain and ground flux to be minimal in
Antarctica (Hock et al., 2005).
Although overall changes in the energy balance over the ice sheet are relatively small, the spatial patterns are coherent.. All
fluxes are defined positively when directed towards the surface, and mean seasonal values for each element of the energy
330   balance are provided as a reference for winter (Supplemental Fig. 7) and summer (Supplemental Figure 8). Additionally, full
comparison of energy balance components comparing values to ERA5 are provided for winter (Supplemental Figure 9) and
summer (Supplemental Figure 10).

3.4.1 Winter

In winter, when incoming shortwave radiation is negligible, net longwave radiation emitted from the surface is a
335   balance between incoming downward and outgoing cooling longwave radiation, with the deficit partially accounted for by
changes to sensible heat flux. During winter, ANTSI shows an increase in LW_{down} over the majority of the continent (Fig.
11d); where biases are positive over the ice sheet, mean winter ANTSI values are 6.78 ±3.36 W m^{-2} larger than AMIP
(consistent with the warmer atmosphere in ANTSI) However, LW_{net} shows only a slight increase over East Antarctica and a
decrease over much of West Antarctica. Over the ice sheet, positive biases for LW_{net} average only 1.88 ± 1.57 W m^{-2},
340   implying an increase in outgoing longwave radiation which produces enhanced surface temperatures shown in Fig. 8c. This
deficit is balanced partially by compensatory changes in sensible heat flux (Fig. 11a), with a mean positive bias compared to
AMIP of 6.12 ± 9.98 W m^{-2} and a mean negative bias of -2.75 ±5.35 W m^{-2} .

Over the majority of the ocean domain in winter, ANTSI produces an increase in LW_{down} (mean positive biases are
2.71 ± 2.67 W m^{-2}), LW_{net} (mean positive biases are 2.06 ± 2.28 W m^{-2}) and sensible heat flux (mean positive biases are 3.22
345   ± 3.87 W m^{-2}, mean negative biases are -3.40 ± 5.53 W m^{-2}), where the Amundsen Sea sector and Weddell Sea sector show
the reverse of the larger spatial pattern. Latent heat flux is reduced over the larger portion of the ocean (negative biases are -
4.40 ± 5.95 W m^{-2}), corresponding to greater latent heat flux from the ocean towards the atmosphere, excepting sections of
the Indian Ocean at lower latitudes.

Because SSTs and SICs were forced from observations in this model run, we assume that this behavior is the result
350   of changes in wind patterns and temperature produced by enhanced resolution over the ocean domain. As compared to ERA5

reanalysis, the bias changes in energy balance components in winter are relatively minor except for downward longwave radiation, where the enhanced resolution produces greater agreement with ERA5 over East Antarctica; the mean negative bias over the ice sheet, as compared to ERA5, decreases from -9.38 ± 4.91 W m^{-2} (AMIP) to -4.56 ± 2.56 W m^{-2} (ANTSI). The only degradation in winter is a slight increase in mean positive biases (Table 2). We note, in light of the total cloud
355   liquid water path in ANTSI showing greater disagreement with ERA5, that the relationship between cloud liquid water path and downward longwave radiation is not one-to-one. In the aggregate, we conclude that the radiation balance in winter is improved with enhanced spatial resolution.

[Table 2]

[Figure 11]

360   **3.4.2 Summer**

In summer (DJF), enhanced LW$_{down}$ in ANTSI is also greater than in AMIP, though the bias is muted as compared to winter, extending over most of the ocean domain except for the Weddell Sea sector and over East Antarctica. Mean summer biases (ANTSI - AMIP) are less than 4 W m^{-2} over the ocean as well as over the ice sheet. Over the margins of the ice sheet and West Antarctica, LWdown is reduced, partially matching the pattern of reduced total liquid cloud path (Fig. 7b). Over most
365   of the ocean, net and downward longwave radiation are both positive, implying that LW$_{down}$ is not entirely balanced by longwave cooling (LW$_{up}$)

Over the majority of the ice sheet, we show a reduction in LW$_{net}$, as LW$_{up}$ exceeds the surplus LWdown . LW$_{down}$ is reduced over the ocean (nearly by 20 W m-2 in regions of the Indian and Pacific sector) and over the center of the East Antarctica, but greatly increased over the margins as well as the Weddell Sea sector (nearly 15 W m^{-2} in some regions), the
370   latter conforming with cloud clearing due to the higher topographic barrier. SW$_{net}$ decreased substantially over the ocean and increased over the ice sheet.

In comparison to ERA5, the biases over oceans for LW$_{down}$, LW$_{net}$, SW$_{down}$ and SW$_{net}$ increase in ANTSI (Fig. 12, Table 3, Supplemental Figures 9 and 10). Over the ice sheet, biases show a distinct spatial pattern, with the bias sign reversing between the high plateau in East Antarctica vs West Antarctica and the margins of the ice sheet. In the aggregate,
375   the radiation balance is improved or changed only slightly, with mean biases reduced (Table 3) biases within ANTSI falling within one standard of the ERA5 mean (Supplemental Fig. 10h,i,n,o,q,r). The exception is SW$_{net}$ (generally a positive bias), where ANTSI biases are higher overall.

In summary, during summer, the representation of the radiation balance show reduced biases as compared to ERA5 over the ice sheet (with the exception of net shortwave radiation), but over the ocean, biases in both shortwave and longwave
380   radiation have increased within ANTSI. One exception to this generalized spatial pattern is the Weddell Sea sector, where the better-resolved (higher) Antarctic Peninsula blocks westerly flow.

[Table 3]

[Figure 12]

4. Discussion and Conclusions:

385

We find that enhancing resolution over the larger Southern Ocean domain, including the Antarctic ice sheet, generally reduces biases in comparison to reanalysis, except with regard to the formation of clouds over the larger Southern Ocean domain. Temperature and wind speed biases (both near-surface and aloft) are largely reduced over both the ocean and the ice sheet, and surface mass balance estimates are generally equivalent, except for over the Antarctic Peninsula. Here, the

390 enhanced resolution resolves the spine of the Antarctic Peninsula mountain range to over 400m greater height, resulting in enhanced precipitation on the western side and reduced precipitation, lower temperature and decreased surface melt on the eastern side as well as over the Weddell Sea sector. In comparison to the ice-core-based reconstruction as well as the regional climate model RACMO2, SMB biases from both datasets produce similar spatial patterns for changes in bias over the AP, West Antarctica and some regions of East Antarctica. There is better agreement between the enhanced resolution

395 model (ANTSI) and the reference datasets over lower-elevation regions in West Antarctica and sections of East Antarctic nearest to the Ronne-Filchner and Ross ice shelves, while biases have increased over the Dronning Maud Land region of East Antarctica. These changes are primarily driven by greater precipitation in these regions driven by enhanced meridional vapor transport from the oceans, especially in winter.

While temperature, wind (both zonal and meridional), specific humidity and total cloud ice water path over the

400 ocean are improved, biases are increased for total cloud liquid water path (TCLWP) over the ocean region in both summer and winter, with a concurrent decrease in downward/net shortwave and increase in downward/net longwave in summer. Over the ice sheet, TCLWP biases are higher in winter as compared to ERA5, but the increase in downward longwave radiation (partially affected by TCLWP) amounts to a reduction in bias compared to ERA5. By contrast, summer TCLWP is higher at the margins, but lower in the interior of the ice sheet, a pattern conforming to changes in orographic precipitation produced

405 by enhanced resolution reported by Kampenhout (2019). The summer pattern for biases in downward/net longwave and downward shortwave (but not net shortwave) indicate reduced biases with regard to AMIP simulations. The change in downward shortwave radiation and higher temperatures may result in the other main enhanced bias, namely the increase in surface melt over most ice shelves, excepting the eastern side of the Antarctic Peninsula (where temperatures are kept lower by the orographic barrier). We note that only for a few ice shelves does this represent a substantial relative increase, as

410 compared to the already-high bias between the coarser-resolution AMIP and observations (QuikSCAT), namely over the Brunt and interior of the Ross ice shelves. The increased surface melt alsos represents an improvement in bias compared to QuikSCAT over the Amery and Shackleton ice shelves (where coarser-resolution simulations underpredict surface melt).

Biases are largely reduced in the near-surface atmosphere over the ice sheet and ocean. However, we posit that the physics of cloud formation (and resultant precipitation), especially over the ocean, are currently better-suited to the coarser resolution

415 model. Future improvements to CAM may benefit from examining how paramaterizations affect cloud formation over the

Southern Ocean in particular, where there are few land masses and where the enhanced availability of precipitation can strongly impact surface mass balance over the ice sheet. Currently, tuning for CESM2 has focused on the standard 1° grid that AMIP uses, while future parameterizations will account for the effects on variable-resolution grids (including ANTSI). We also note the possibility that these biases may be alleviated with the activation of the ocean component of CESM2, rather

420 than the one-way forced sea surface temperature and sea ice concentration formulation used in these simulations.

Accounting for these biases, this work suggests that the variable-resolution setup over Antarctica can be a valuable tool for representations of precipitation, surface mass balance, and therefore sea level rise estimates over Antarctica. In particular, the enhanced resolution better articulates spatial patterns associated with orographic precipitation which may capture fine-scale changes in precipitation patterns in simulations of future warming scenarios. We note that the improvements over Antarctica

425 are less pronounced than those shown over Greenland, where they are significant (van Kampenhout et al., 2019). The enhanced resolution grid can capture these changes while preserving two-way interaction with the larger global climate system, but at a reduced computational cost (as compared to global high-resolution runs). However, we note that some regional climate models such as RACMO2.3 (van Wessem et al., 2018) or the MAR model (Agosta et al., 2019) typically contain much more sophisticated representations of the firn layer as well as more sophisticated albedo schemes. For studies

430 specifically focused on the effects on the two-way interactions with firn, RCMs such as RACMO2.3 or MAR may provide better value overall. For these ANTSI runs, we note that outputs have been produced at 3-hourly intervals that could potentially force sophisticated firn models with even finer representation of firn layers than RCMs. Similarly, despite a poorer representation of the firn layer, very high-resolution non-hydrostatic models (Gilbert et al., 2022) best capture wind and temperature dynamics over the East Antarctic Peninsula, e.g. foehn flow. While the variable-resolution domain provides

435 substantial value for experiments fully utilizing the two-way interaction between the interior and global domain, they do not replace RCMs.

The improvements with enhanced resolution over the larger Southern Ocean domain are relevant to future work. While the evaluation of the ANTSI grid focuses on the 1979-2014 period (to match available AMIP results), model results for ANTSI are available for the 2015-2020 period, during which we have implemented moisture-tagging as well, connecting

440 precipitation to its sources on the globe. As extreme events constitute a substantial portion of precipitation over the Antarctic ice sheet (Dalaiden et al., 2020), enhanced resolution may offer better insights into the behavior of extreme events as well as mean behavior. In future work, we will be presenting the climatology of atmospheric rivers produced by these outputs at the ANTSI resolution, their associated precipitation, and its moisture sources. Variable resolution grids allow us to avoid the computational cost of high-resolution global models while preserving the two-way interaction with other earth systems. We

445 anticipate the use of the ANTSI grid in fully-coupled runs for future climate scenarios, better constraining precipitation over the Antarctic ice sheet and thus future estimates of sea level rise.

Data availability:

All outputs used for this evaluation are available through Zenodo: https://doi.org/10.5281/zenodo.7335892

Author contribution:

450   RTD performed simulations and major analysis. AH provided substantial guidance about the usage of VRCESM2. JTML provided initial guidance on the project design. DS provided input on analysis. ZY provided input on the final manuscript. DD provided input on initial versions of the manuscripts.

Competing Interests:

The authors declare that they have no conflict of interest

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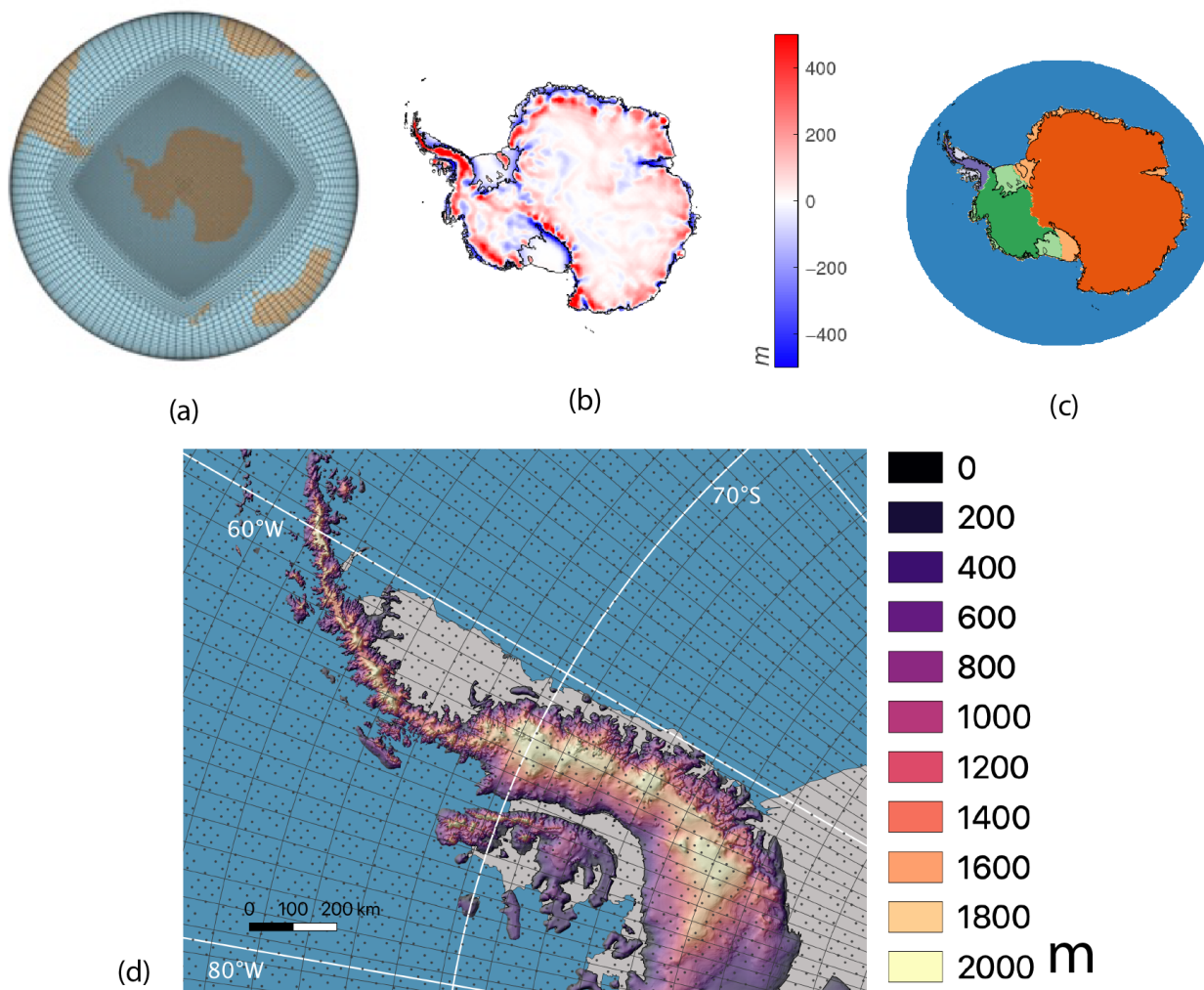
Figure 1: Elevation (a) the ANTSI grid with 0.25° spectral element points in the interior and 1° in the exterior (b) Difference between interpolated surface elevation (ANTSI-AMIP) (c) regions shown for East Antarctica (orange), West Antarctica(green) and the Antarctic Peninsula (purple) with lighter shades indicating ice shelves and darker shades indicating the grounded ice sheet, from Zwally et al., 2002 (d) Elevation (source: ETOPO), AMIP grid shown in lines, ANTSI spectral element points shown in dots over the Antarctic Peninsula

Region	Full		Grounded Ice Sheet		Ice Shelves	
model	AMIP	ANTSI	AMIP	ANTSI	AMIP	ANTSI
E. Ant	1492.93 (± 43.57)	1583.66 (±101.93)	1283.83 (± 38.26)	1394.32 (± 91.25)	209.10 (±7.29)	189.35 (± 17.86) -0.80 GT yr^{-2}
W.Ant	909.47 (±41.30)	933.49 (±72.34)	696.88 (±33.98)	727.66 (±59.74)	212.59 (±8.51)	205.84 (±15.08)
AP	112.99 (±6.40) 0.29 GT yr^{-2}	151.17 (±13.28) 0.56 GT yr^{-2}	71.81 (± 4.34) 0.24 GT yr^{-2}	106.38 (±10.48) 0.51 GT yr^{-2}	41.18 (±2.49)	44.79 (±5.10)
ALL	2515.39 (±53.14)	2668.32 (±123.10)	2052.2 (±44.89)	2228.35 (±111.77)	462.87 (±11.32)	439.97 (±20.56)

Table 1: Surface mass balance values (in GT/yr) for each region, model source as listed. Interannual trends shown in red using the Mann-Kendall test where p values are < 0.05

635
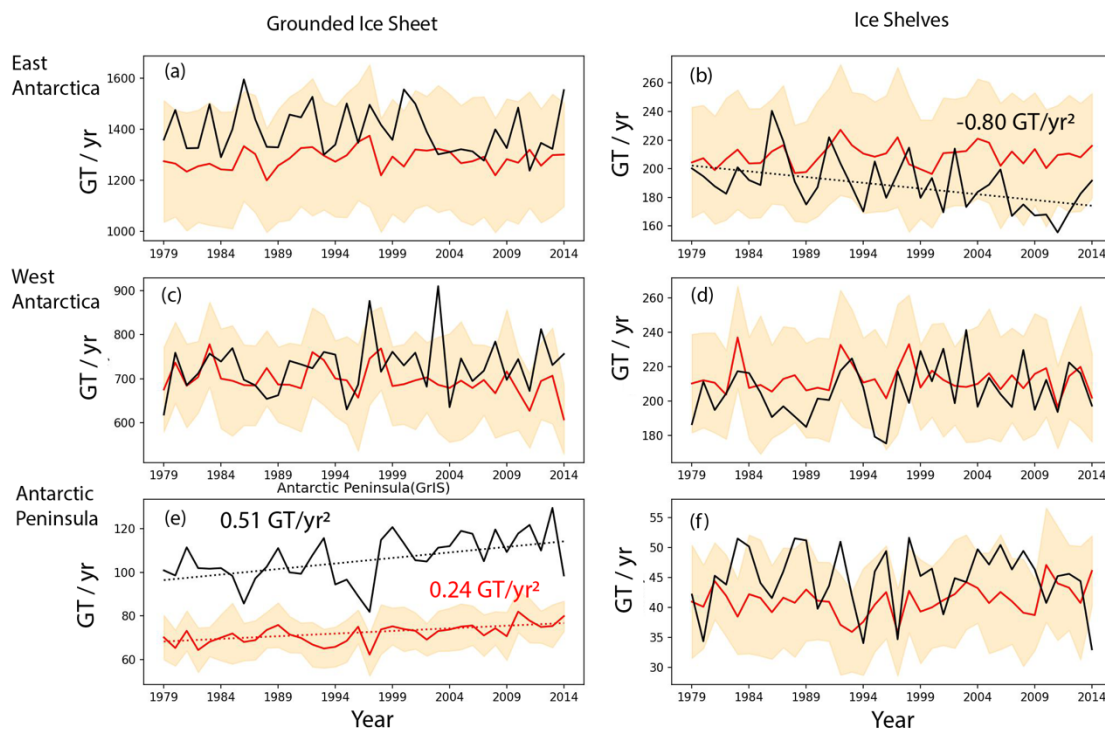
Figure. 2 Integrated surface mass balance for AMIP (mean shown in orange line, one standard deviation shown in orange shade) vs ANTSI (black line) for (a) East Antarctic Grounded Ice Sheet (b) East Antarctic Ice Shelves (c) West Antarctic Grounded Ice Sheet (d) West Antarctic Ice Shelves (e) Antarctic Peninsula Grounded Ice Sheet (f) Antarctic Peninsula Ice Shelves. Trend lines shown where the Mann-Kendall trend test p-value < 0.05

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(a)

(b)

(c)

(d)

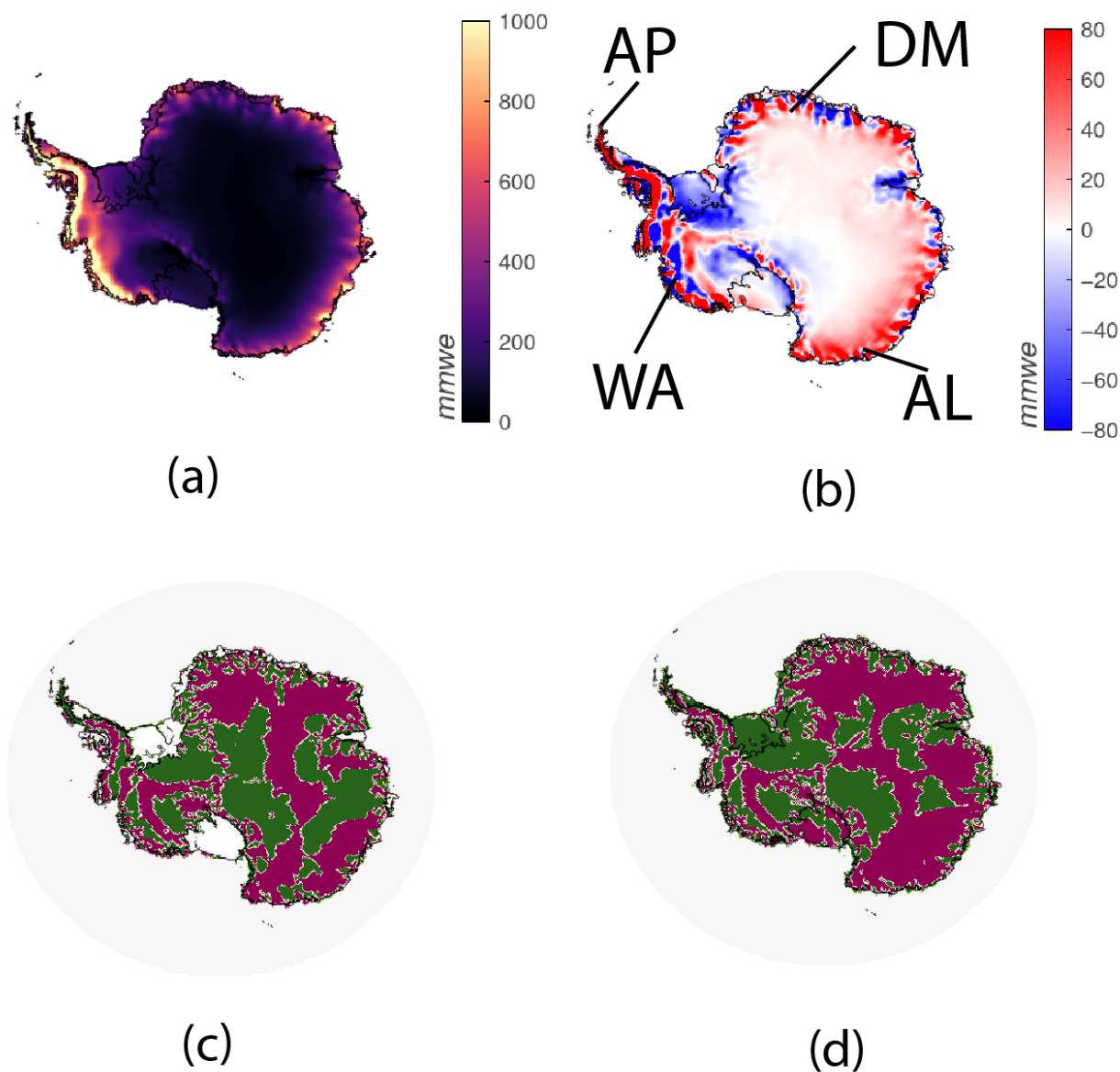



Figure 3. Surface mass balance (SMB) over the 1979-2014 period. (a) SMB from ANTSI (b) difference in SMB (ANTSI-AMIP).
Regions indicated include the Antarctic Peninsula (AP), Dronning Maud Land (DM), West Antarctica (WA) and Adelie Land
(AL). Regions of increased/decreased bias as compared to outside sources where green indicates where SMB bias is reduced in
645 **ANTSI (vs AMIP), purple indicates where SMB bias increased in ANTSI (vs AMIP). (c) As compared to Medley Reconstruction**
(d) As compared to RACMO2.3

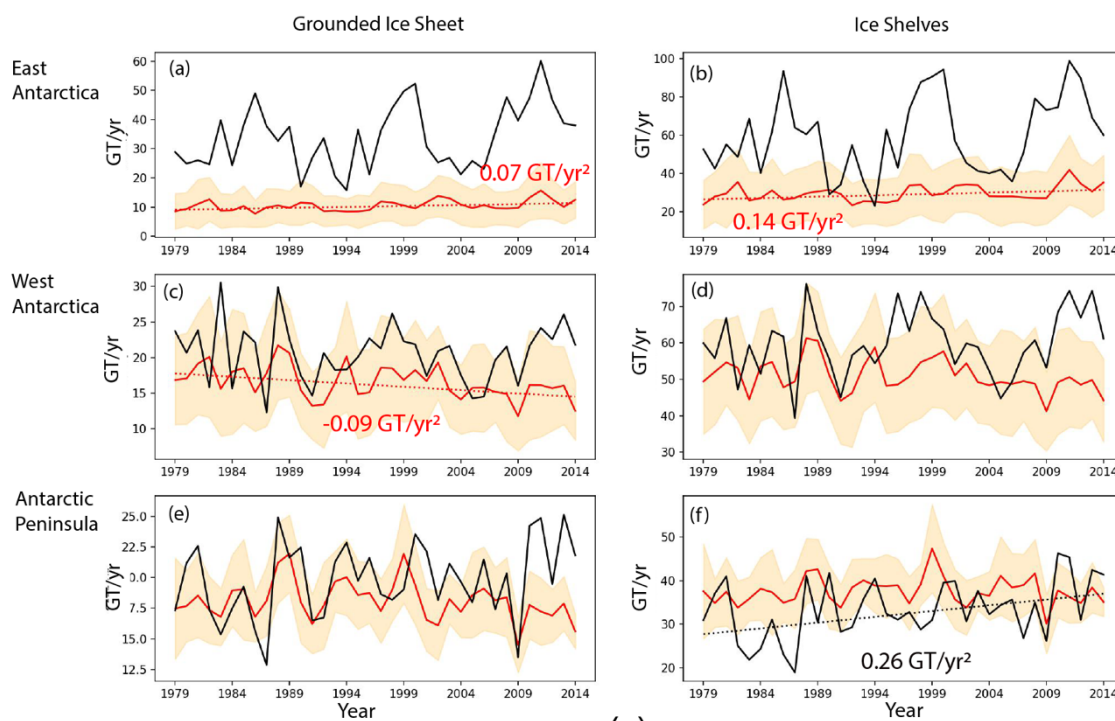
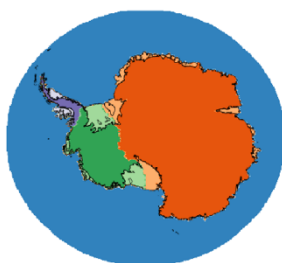



Figure 4: (a) Surface melt (in GT yr-1) shown (b) Regions for East Antarctica (orange), West Antarctica (green) and the Antarctica Peninsula (purple), with darker colors indicating the grounded ice sheet and lighter colors indicating ice shelves. Based on Zwally et al. 2002

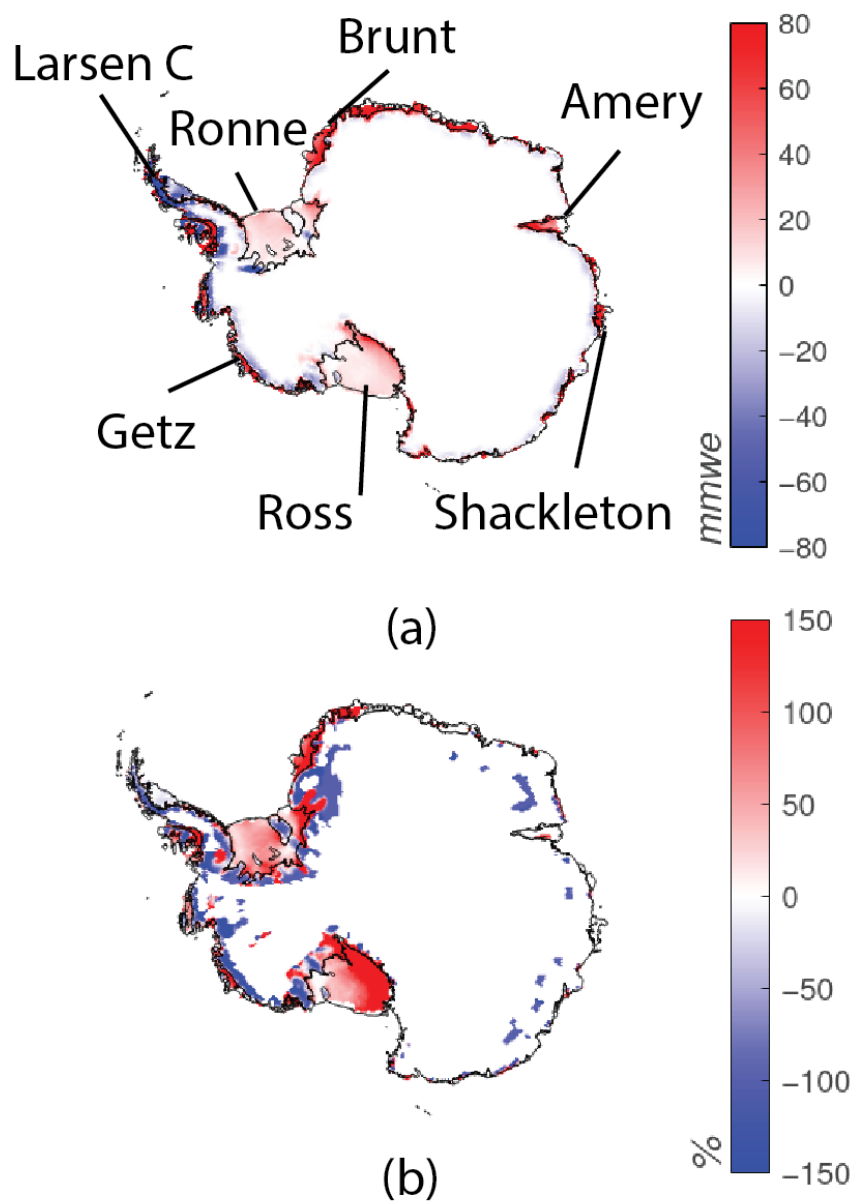



Figure 5: Changes in surface melt with resolution. (a) Mean difference in surface melt (ANTSI − AMIP), with individual ice shelves indicated (b) Where AMIP surface melt shows a positive bias as compared to QScat, the relative difference between models as a percentage of the difference between the coarse resolution model and the observationally-based reference, i.e. (ANTSI − AMIP)/(AMIP-QSCAT).

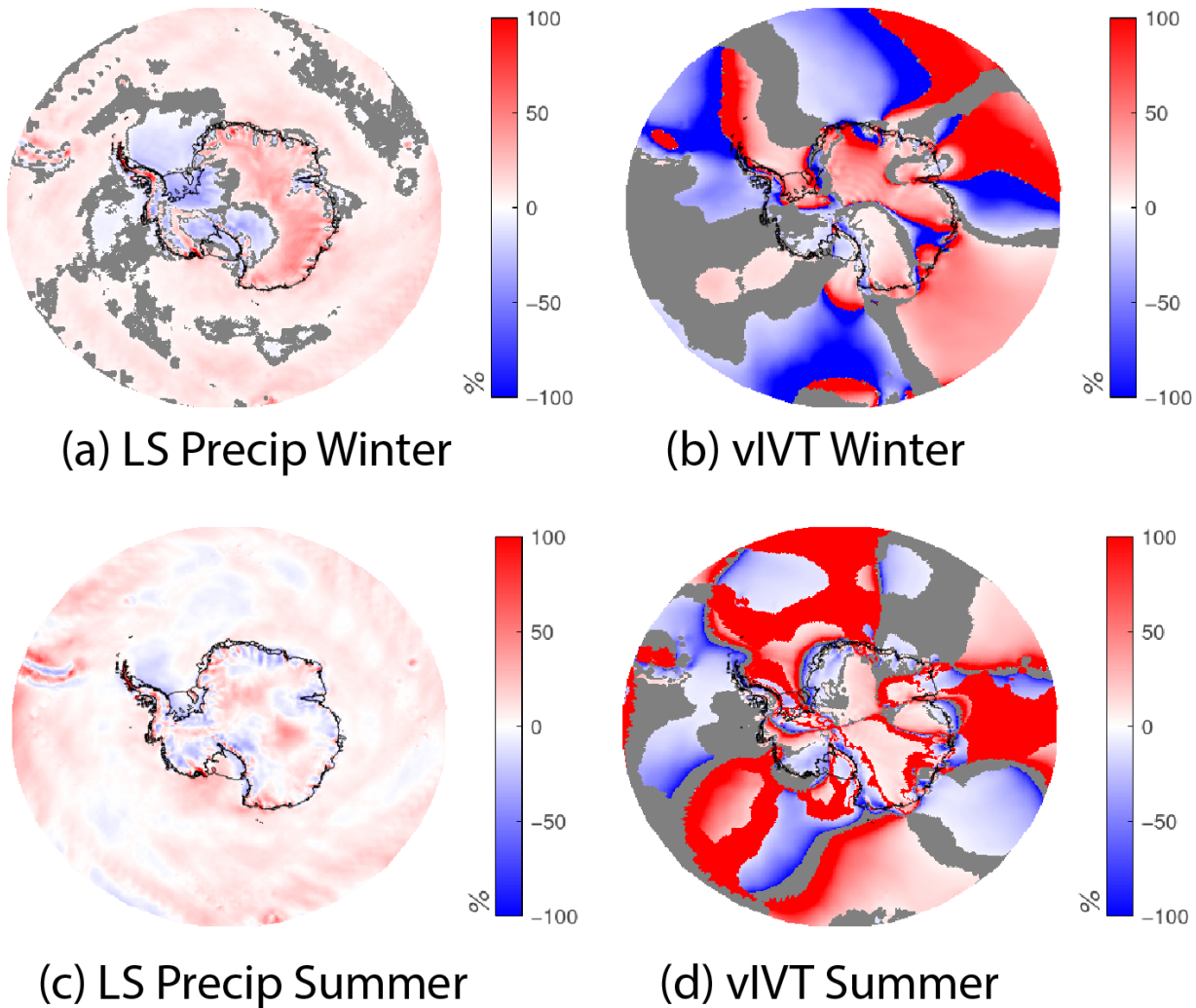



Figure 6: Relative change (%) in precipitation and integrated meridional vapor transport between ANTSI and AMIP, 1979-2014 seasonal mean. (a) large-scale precipitation for winter (JJA) and (c) summer (DJF). Integrated meridional vapor transport for winter (b) and summer (d)

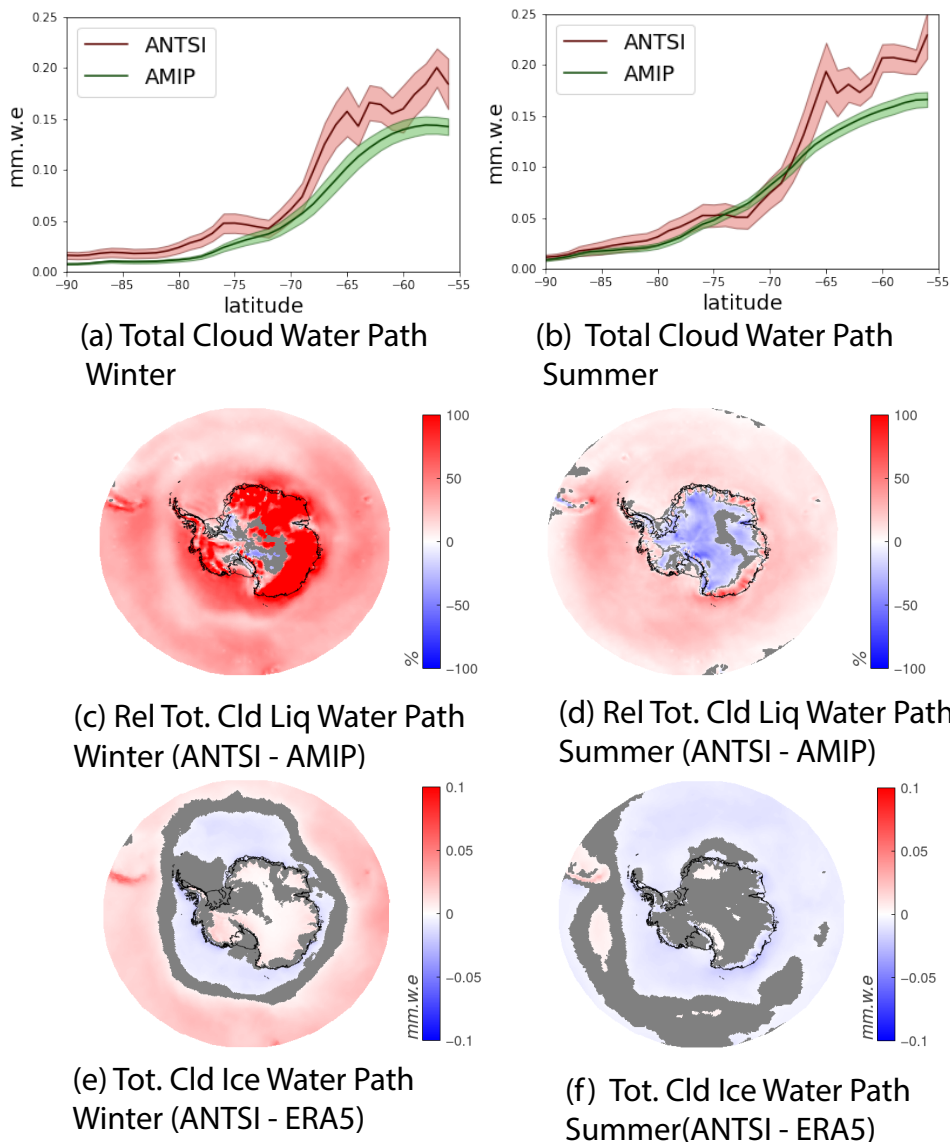



Figure 7: Cloud water path. Total cloud water path aggregated in latitude bands (shaded area shows temporal standard deviation) for (a) winter, JJA (b) Summer, DJF. Relative difference in change between ANTSI and AMIP (in percentage) in total cloud liquid water path for seasonal mean (1979-2014) for winter, JJA (c) and summer, DJF (d). Absolute difference in change between ANTSI and ERA5 reanalysis in total cloud ice water path for seasonal mean (1979-2014) for winter, JJA (e) and summer, DJF (f)

(a) DJF (ANTSI - AMIP)   (b) DJF (ANTSI - ERA5)

(c) JJA (ANTSI - AMIP)   (d) JJA (ANTSI - ERA5)

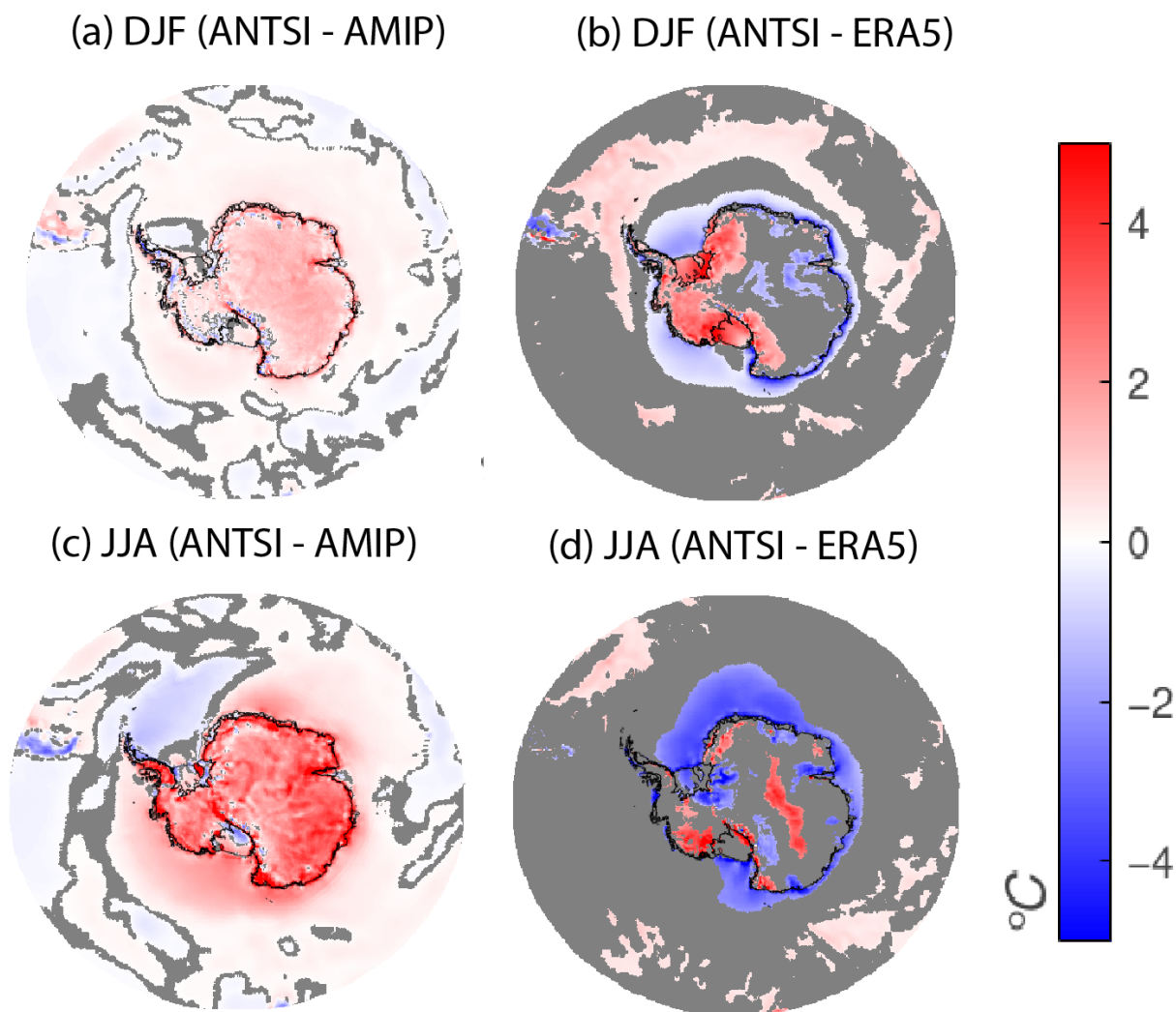



Figure 8. Near surface temperature comparisons between models and reanalysis. (a) DJF ANTSI-AMIP (b) DJF ANTSI - ERA5 (c) JJA ANTSI-AMIP (d) JJA ANTSI-ERA5 where difference exceeds one standard deviation of AMIP ensemble mean.

670

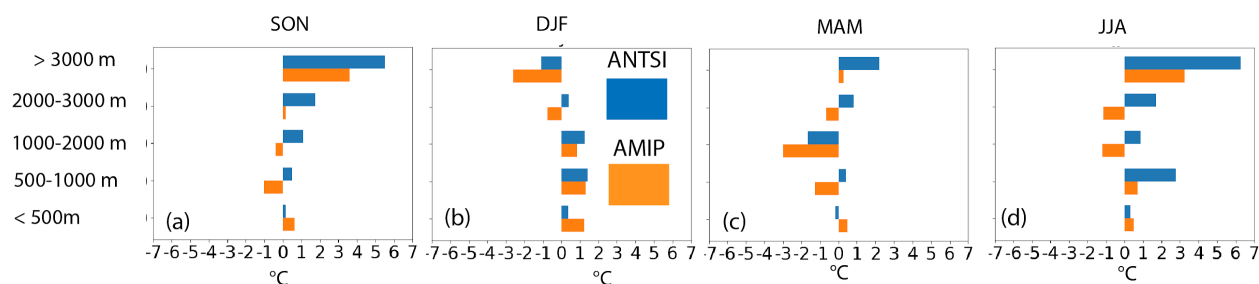



Figure 9: Near-surface temperature comparisons with AWS stations. Comparing temperature biases as compared to AWS stations, binned into elevation classes (a) SON (b) DJF (c) MAM (d) JJA

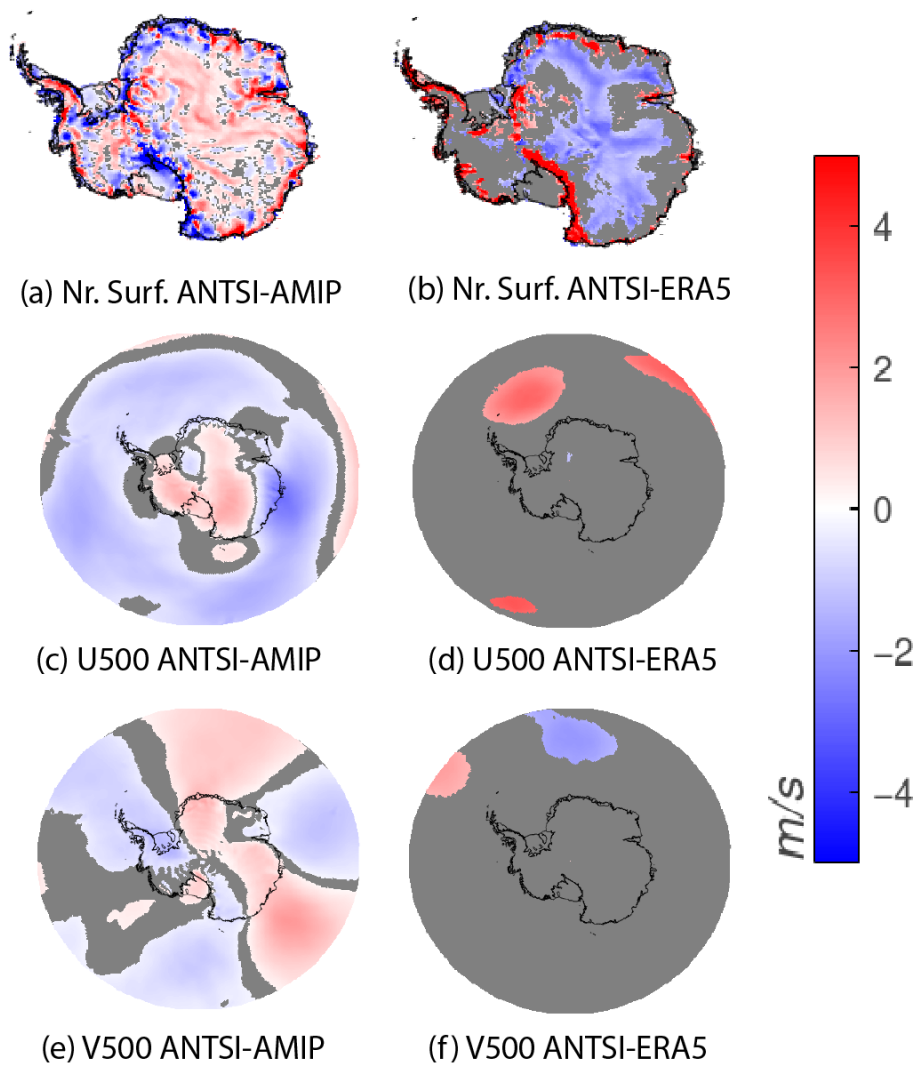



Figure 10. Mean winter (JJA) wind speed differences (1979-2014) between ANTSI-AMIP (left column) and ANTSI-ERA5 (right column) for the near-surface (a)(b), the 500 hPa zonal component (c)(d) and the 500 hPa meridional component (e)(f)

	Ocean		Ice sheet	
	LW$_{down}$	LW$_{net}$	LW$_{down}$	LW$_{net}$
AMIP – ERA5				
Positive bias	10.72 ±6.23	10.29 ± 5.19	5.11 ± 5.18	5.22 ± 4.44
Negative bias	-4.29 ±5.53	-7.70 ± 7.81	-9.38 ± 4.91	-6.55 ± 5.31
ANTSI – ERA5				
Positive bias	**10.78 ± 6.34**	**10.51 ± 5.52**	**4.60 ± 3.67**	**4.25 ± 4.04**
Negative bias	**-4.27 ± 5.50**	**--6.38 ± 6.79**	**-4.56 ± 2.56**	**-6.16 ± 5.44**

685 **Table 2: Mean and standard deviation of downward and net longwave radiation (model - ERA5) in winter (JJA). Values are calculated separately for the sign of bias (positive and negative) and for the ocean (below -55° latitude) vs. the ice sheet. Bias improvement is shown in green and degradation in red.**

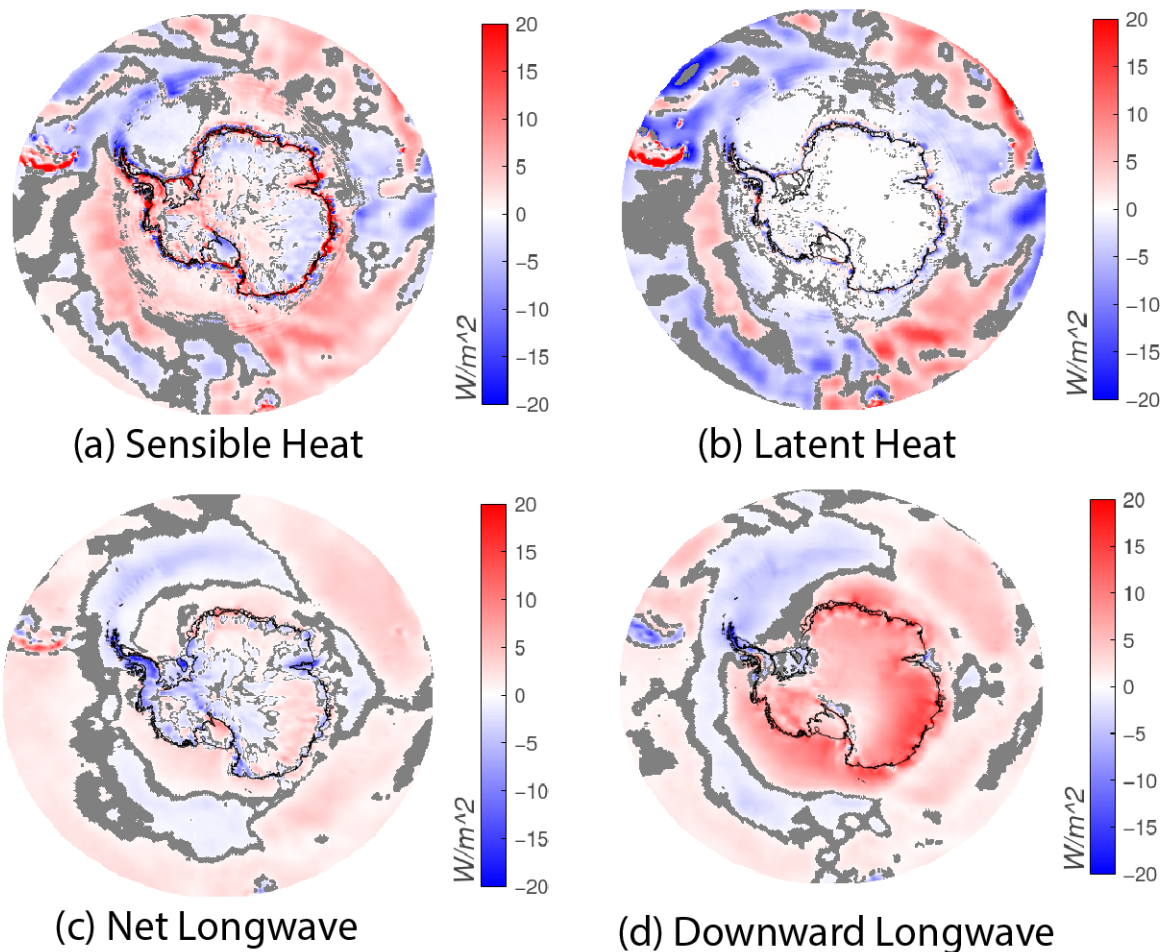



Figure 11: Mean differences (ANTSI-AMIP) in the winter (JJA) radiation balance (1979-2014) for (a) Sensible Heat Flux (b) Latent Heat Flux (c) Net Longwave Radiation (d) Downward Longwave Radiation. All fluxes are directed downward.

	Ocean				Ice sheet			
	LW$_{down}$	LW$_{net}$	SW$_{down}$	SW$_{net}$	LW$_{down}$	LW$_{net}$	SW$_{down}$	SW$_{net}$
AMIP-ERA5								
Positive bias	12.63 ±6.21	12.08 ±5.95	13.21 ± 10.47	13.72 ± 10.69	12.59 ± 8.49	7.85 ± 6.31	8.91 ± 5.96	6.60 ± 4.88
Negative bias	-5.75 ±4.95	-6.83 ±6.24	-28.36 ±17.74	-27.25 ±16.58	-5.96 ± 3.69	-4.21 ± 2.77	-14.72 ± 11.28	-20.18 ± 24.80
ANTSI-ERA5								
Positive bias	**13.67 ± 6.89**	**12.89 ± 6.28**	**12.12 ±10.70**	**12.87 ± 10.76**	**11.32 ±6.71**	**5.90 ± 4.81**	**7.42 ± 4.95**	**8.13 ± 5.79**
Negative bias	**-4.83 ± 4.95**	**-5.82 ± 5.52**	**-33.00 ± 20.08**	**-32.04 ± 1964**	**-3.50 ± 2.20**	**-4.27 ±3.05**	**-11.82 ± 9.34**	**-23.66 ± 24.98**

700

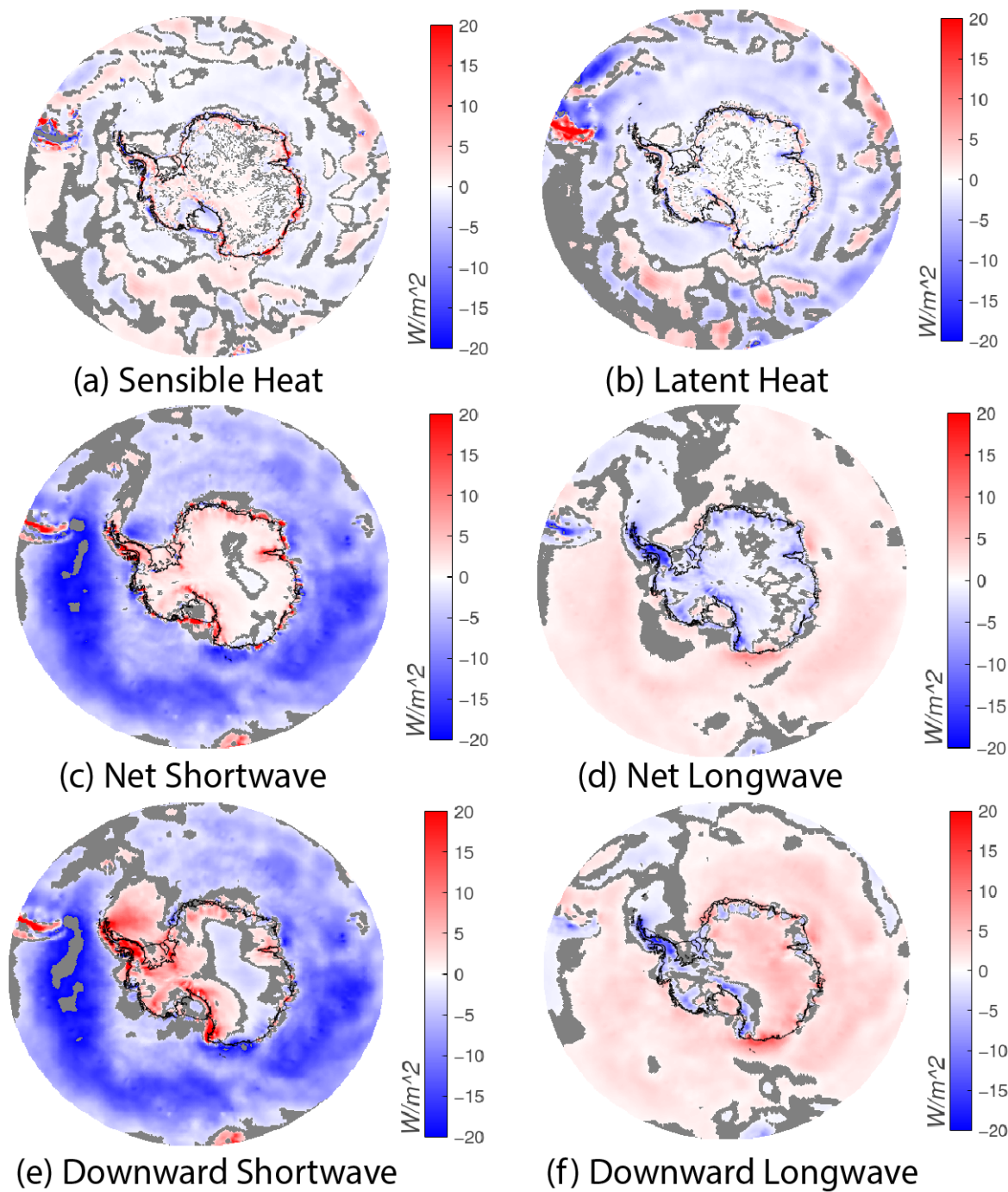
Table 3: Mean and standard deviation of downward and net longwav eand shortwave radiation (model - ERA5) in winter (DJF). Values are calculated separately for the sign of bias (positive and negative) and for the ocean (below -55° latitude) vs. the ice sheet. Bias improvement is shown in green and degradation in red.

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Figure 12: Mean differences (ANTSI-AMIP) in the summer (DJF) radiation balance (1979-2014) for (a) sensible heat flux (b) latent heat flux (c) net shortwave radiation (d) net longwave radiation (e) downward shortwave radiation, (f) downward longwave radiation. All fluxes are directed downward.