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20th-Century Antarctic Sea Level Mitigation Driven by Uncertain East Antarctic Accumulation History

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Key Points:

- Antarctic accumulation reconstruction using paleoclimate data assimilation finds modest (∼1 mm) 20th-century sea level mitigation
- We find similar 20th-century trends to previous work; lower sea level mitigation (1 vs. 10 mm) is due to the 19th-century baseline
- Uncertainty in past East Antarctic accumulation limits confidence in future projections of Antarctic sea level mitigation

Supporting Information:

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

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Abstract

Increasing snow accumulation over the Antarctic Ice Sheet may mitigate future sea level rise. However, current estimates of mitigation potential are poorly constrained due to limited records of past variability. We present an annually resolved reconstruction of Antarctic snow accumulation from 1801 to 2000 CE, employing a paleoclimate data assimilation methodology to integrate ice core records with a multi-model ensemble of climate simulations. Our reconstruction correlates well with instrumental reanalysis, and we find that Antarctic accumulation rates increased over the 20th-century, resulting in a modest amount (∼1 mm) of sea level mitigation. Mitigation is primarily driven by an accelerating trend since around 1970. Our results contrast with previous mitigation estimates of ∼10–12 mm; this discrepancy is due to poorly constrained baseline estimates of 19th-century accumulation in East Antarctica. Our reconstruction suggests that the uncertainty of future sea level mitigation from increasing Antarctic accumulation has been underestimated.

Plain Language Summary

Ice loss from Antarctica causes sea level to rise, but Antarctica can also mitigate sea level rise if snowfall on the continent increases faster than the ice loss. There is not currently a consensus on whether Antarctica will contribute to or mitigate sea level rise in the coming century, due to a lack of Antarctic snowfall records. In this paper, we merge information from ice core records with climate models to reconstruct annual Antarctic snowfall from 1801 to 2000. We find that snowfall on Antarctica increased during the 20th-century, but only had a modest counteracting effect of 1 mm on sea level rise in the 20th-century, much less than a previous estimate of 10 mm. The large discrepancy is due to uncertainty in East Antarctic accumulation in the 19th-century. The potential for Antarctica to mitigate sea level is uncertain, affecting projections for future sea level rise.

1. Introduction

Projections of future sea level contribution from the Antarctic Ice Sheet (AIS) are highly uncertain, with existing studies disagreeing on the sign of the contribution (Edwards et al., 2021; Payne et al., 2021; Seroussi et al., 2020; Siahaan et al., 2022). The Antarctic contribution to global mean sea level change is primarily driven by two competing processes: a positive contribution (raising sea level) from ocean-driven ice mass loss at the margins of the ice sheet and a negative contribution (lowering sea level) from increased snow accumulation at the surface. In response to warming temperatures over Antarctica, both ice-shelf basal melting (Golledge et al., 2019; Levermann et al., 2020) and snow accumulation (Frieler et al., 2015; Lenaerts et al., 2016) are projected to increase. However, studies of the Antarctic temperature-accumulation relationship have indicated a wide range in sensitivity (e.g., Fudge et al., 2016), and that general circulation models may be overestimating the increased snowfall due to warming (Nicola et al., 2023).

Since the late 20th-century, Antarctica has undergone both significant warming (Nicolas & Bromwich, 2014; Steig et al., 2009) and ice sheet mass loss (Rignot et al., 2019; Shepherd et al., 2018). However, 20th-century Antarctic accumulation trends, and their impact on global mean sea level, remain poorly understood. Satellite observations of ice sheet mass change span only recent decades (e.g., Pritchard et al., 2009; Smith et al., 2020); furthermore, instrumental reanalysis products are unreliable prior to the satellite era (Schneider & Fogt, 2018). Ice core records can be used to infer past accumulation, but are spatially restricted point measurements that must be extrapolated across Antarctica to gain insight relevant to global sea level change. Reconstructions that combine ice core data with dynamically consistent spatial interpolation are limited in number, and different methodologies yield conflicting results: either an insignificant 20th-century Antarctic accumulation trend (Frezzotti et al., 2013;

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Monaghan et al., 2006) or a significant accumulation increase contributing to sea level mitigation (Dalaiden et al., 2020; Medley & Thomas, 2019; Thomas et al., 2017; Wang & Xiao, 2023).

Paleoclimate data assimilation is a powerful framework for generating spatially complete climate reconstructions from geographically sparse proxy data sets. Combining both spatial information from climate models and temporal information from proxy records, this approach offers greater versatility than alternate statistical methods, improves compatibility with the physics of the climate system, and provides a robust framework for uncertainty quantification (Hakim et al., 2016; Klein et al., 2019). To our knowledge, only one study (Dalaiden et al., 2020) has employed a data assimilation methodology to reconstruct Antarctic accumulation; alternate studies have instead relied on extrapolation of spatial covariance structures within instrumental reanalyzes (Medley & Thomas, 2019; Monaghan et al., 2006; Wang & Xiao, 2023) or construction of regional ice core composites (Frezzotti et al., 2013; Thomas et al., 2017).

The Last Millennium Reanalysis, a well-established data assimilation framework with robust capabilities for reconstructing a wide range of climatic variables (Hakim et al., 2016; Tardif et al., 2019), has previously been adapted for polar reconstructions through incorporation of ice core records from Antarctica (O'Connor et al., 2021) and Greenland (Badgeley et al., 2020). Here, we incorporate a set of 120 ice core accumulation and water isotope records from Antarctica. We reconstruct spatially complete and annually resolved accumulation variability over the AIS from 1801 to 2000 CE, and the equivalent contribution to global mean sea level.

2. Methods

We use offline paleoclimate data assimilation to produce our accumulation reconstructions. Specifically, we apply the ensemble Kalman filter methodology employed by the Last Millennium Reanalysis framework (Hakim et al., 2016; Tardif et al., 2019; more details in Text S4 of Supporting Information S1). Spatial completeness in the final reconstructions is provided by the climate model "prior" ensemble; priors consist of base model states drawn from historical climate simulations, which supply a geographic covariance structure. We construct a multi-model ensemble ("MME") prior, which amalgamates randomly drawn samples from nine separate CMIP5 Last Millennium (850–1850 CE) climate model simulations (Taylor et al., 2012). We run additional reconstructions with the nine individual Last Millennium simulations; we also test one "postindustrial" (1850–2005 CE) prior (Table S1 in Supporting Information S1; more details in Text S2 of Supporting Information S1).

To convert the "prior" base climate state into the "posterior" final state estimate, we use an ensemble Kalman filter to assimilate novel information from proxy records. In total, we incorporate 120 ice core records (Figures S1 and S2 in Supporting Information S1, more details in Text S1 of Supporting Information S1), including 62 water isotope records (Stenni et al., 2017) and 58 accumulation records (Thomas et al., 2017). A forward model maps the prior state estimate to proxy space, relying on linear regression to the GISS Surface Temperature Analysis (Hansen et al., 2010; more details in Text S3 of Supporting Information S1); to qualify our results, we note that this approach is sensitive to both the observed and modeled temperature-accumulation relationship. Finally, we produce the posterior state estimate: A 250-member ensemble of annually resolved gridded accumulation anomalies from 1801 to 2000. As accumulation in Antarctica is dominated by precipitation (Dalaiden et al., 2021), we assume the two to be equivalent. The anomaly reference period used is the 1951–1980 mean.

The skill of resulting accumulation reconstructions is evaluated by comparison with precipitation output from the instrumental reanalysis ERA5 (Hersbach et al., 2020); the specific comparative metrics used are correlation (r) and coefficient of efficiency ("CE"; Nash & Sutcliffe, 1970) during the satellite era (1981–2000). While reanalysis remains consistently reliable into the present, the ice core record is highly limited (i.e., 20 proxy sites) during the 21st-century (Figure S2 in Supporting Information S1); thus, we end our reconstruction in 2000.

To determine sector-wide accumulation trends, we spatially integrate gridded accumulation over the Antarctic drainage basins defined by Zwally et al. (2012), excluding ice shelves. We convert reconstructed accumulation into the equivalent contribution to global mean sea level by following Medley and Thomas (2019) in integrating the annual accumulation time series relative to the 19th-century mean (more details in Text S5 of Supporting Information S1).

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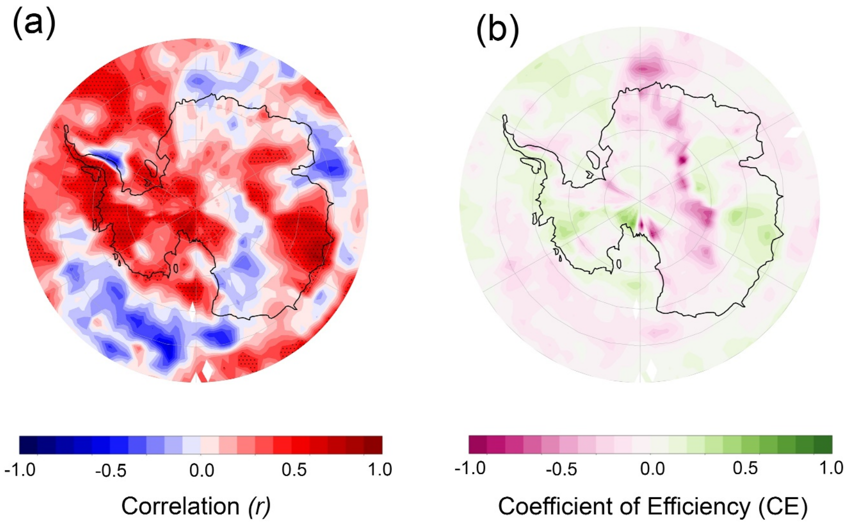

Figure 1. (a) Correlation and (b) coefficient of efficiency between the multi-model ensemble accumulation reconstruction and ERA5 annual precipitation output for the period 1981–2000 CE. Correlation values with $p < 0.05$ are designated with stippling; positive CE values indicate reconstruction skillfulness.

3. Results

3.1. Skill Validation

We analyze the spatial skill of accumulation reconstructions through comparison with ERA5 instrumental reanalysis between 1981 and 2000 CE. In general, highest skill is found around the West Antarctic Ice Sheet (WAIS), Antarctic Peninsula (AP), and Wilkes Land; the lowest skill is found around Dronning Maud Land (DML) and the interior East Antarctic Plateau. The MME demonstrates the highest skill of the tested priors, with the greatest improvements occurring in the low-skill, low accumulation regions of the East Antarctic Plateau (Figures S3 and S4 in Supporting Information S1; Table S1 in Supporting Information S1). This is consistent with a previous finding that multi-model ensembles improve climate reconstruction skill for regions with high uncertainty that are far from proxy sites (Parsons et al., 2021). We present the MME reconstruction from now onwards.

The MME displays high skill ($p < 0.05$; CE > 0) over most of West Antarctica (Figure 1); a spatially weighted average for WAIS gives $r = 0.67$ and CE = 0.33. Skill in East Antarctica is more variable, with much of the East Antarctic Plateau and DML exhibiting a lack of skill ($p > 0.05$; CE < 0; Figure 1). Nevertheless, spatially averaged metrics for the East Antarctic Ice Sheet (EAIS) show reasonable skill, with a positive CE (0.17) and a near-significant correlation ($r = 0.43$; $p = 0.06$). A previous evaluation of precipitation reconstruction potential found skill to be broadly correlated with high accumulation rates (an indicator of higher-quality proxy records) and geographic proximity to proxy sites (Steiger et al., 2017). This relationship holds in our reconstruction; higher skill in WAIS likely reflects denser proxy coverage and higher accumulation rates.

3.2. Reconstructed Accumulation Trends

During the 19th-century, we find no significant trend across any Antarctic sector. However, we find a clear positive trend in Antarctic snow accumulation over the 20th-century. AIS-wide accumulation increased by 0.4 ± 0.1 Gt yr^{-2} from 1901 to 2000, accelerating to 1.1 ± 0.6 Gt yr^{-2} after 1957 (Figure 2a). This trend was principally driven by a late-century acceleration (Figure 2g) in AP and WAIS (Figures 2b and 2d). We find a positive trend in eastern WAIS that dominates a slight negative trend in western WAIS (Figure 2g); this "see-saw" pattern, characteristic of the Amundsen Sea Low, is also found in the reconstructions of MT19, Dalaiden et al. (2020; "D20"), and Wang and Xiao (2023; "WX23").

We find no significant trend in EAIS across any evaluated time period (Figure 2c), although we do find a localized late-century negative trend in coastal DML (Figure 2g). The lack of significant trends in EAIS stands in contrast to

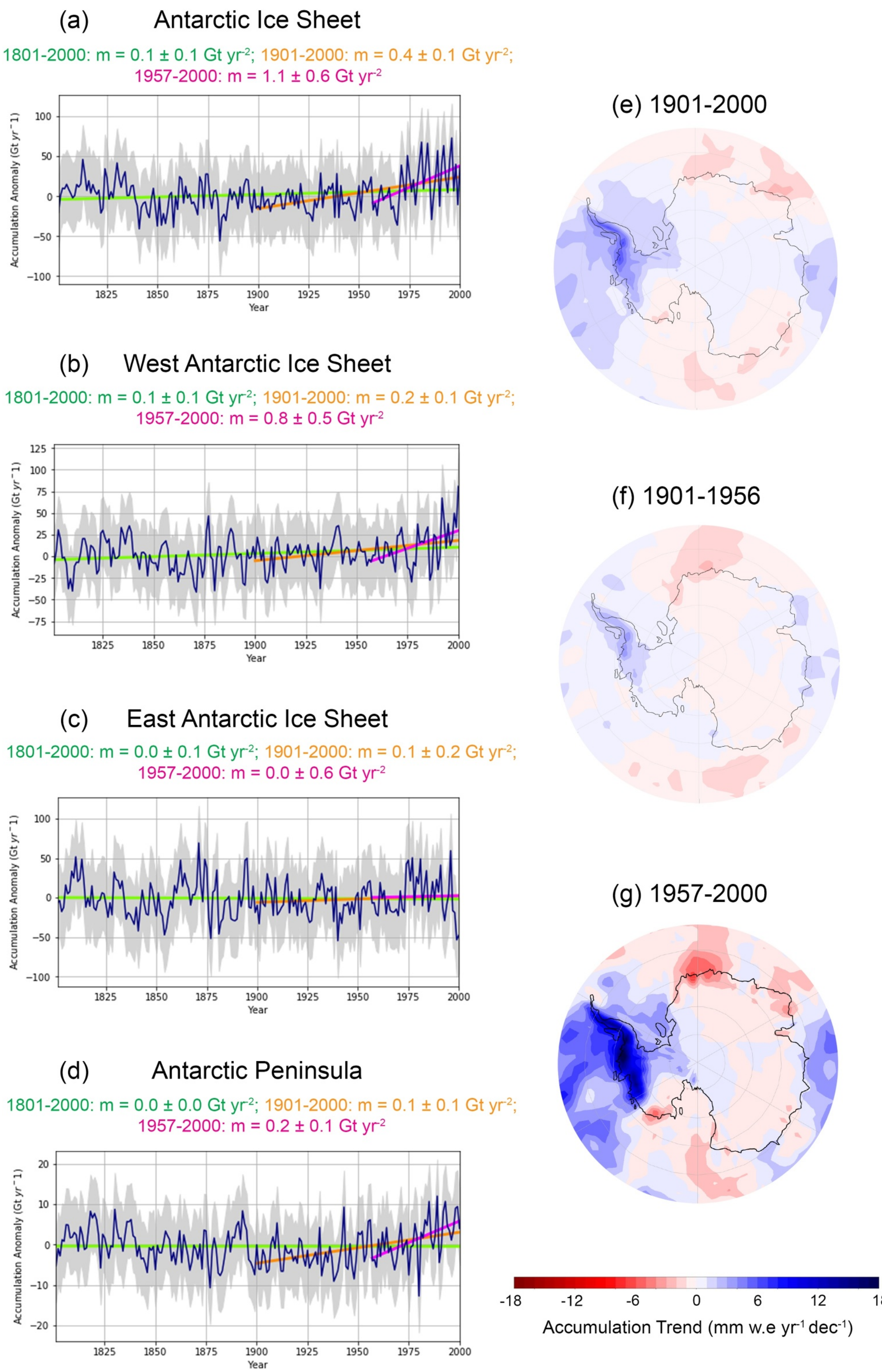

Figure 2. (a–d) Temporal and (e–g) spatial trends in Antarctic accumulation, over the 19th and 20th centuries. Annually resolved accumulation anomalies in (a–d) are shown relative to the 19th-century mean, and represent a spatial integration over the given Antarctic sector. Trendline uncertainties and shaded bounds designate the 95% confidence interval ($\pm 2\sigma$).

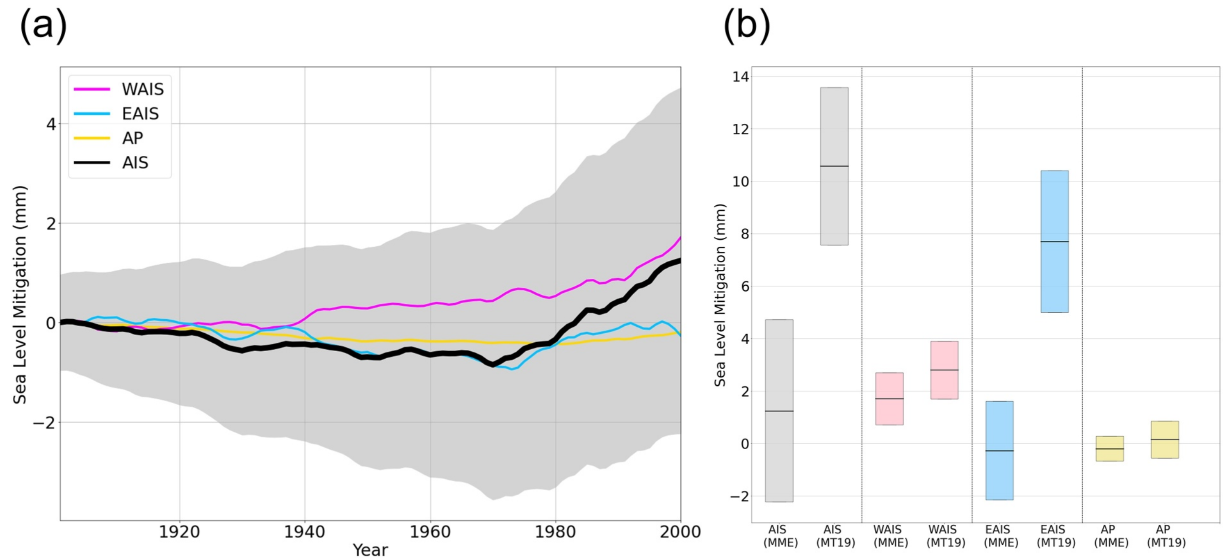

Figure 3. (a) Temporally cumulative sea level mitigation from each Antarctic sector for the period 1901–2000, with the regional 19th-century mean used as the baseline value. Shaded bounds represent the 95% confidence interval for Antarctic Ice Sheet mitigation, accounting for both uncertainty in the 1901–2000 mitigation distribution ($\pm 2\sigma$) and the standard error ($\pm 2\sigma_M$) of the 19th-century mean. (b) Total 20th-century sea level mitigation for each Antarctic sector, with uncertainties shown; our estimates multi-model ensemble are compared to those from Medley and Thomas (2019; “MT19”).

the estimates from MT19, D20, and WX23, all of whom find a statistically significant increase in EAIS accumulation from 1801 to 2000 (Table S3 in Supporting Information S1).

3.3. Sea Level Mitigation

We find that 20th-century AIS sea level mitigation due to snow accumulation (Figure 3a) was insignificant (1.2 ± 3.5 mm), and that WAIS (1.7 ± 1.0 mm) was the only Antarctic sector to definitively mitigate sea level rise (Table 1). We find no significant mitigation from EAIS (−0.3 ± 1.9 mm) or AP (−0.2 ± 0.5 mm). Examination of a more restricted interval (1970–2000) reveals a significant trend. In our reconstruction, AIS mitigated sea level rise from 1970 to 2000 (0.7 ± 0.3 mm dec^{-1}, with a total mitigation of 2.2 ± 0.8 mm), comparably driven by both WAIS (0.3 ± 0.1 mm dec^{-1}) and EAIS (0.3 ± 0.1 mm dec^{-1}); this is a shift from the 1901–1970 period, where we find no significant AIS mitigation trend (Table 1).

Our estimate of 20th-century AIS sea level mitigation is an order of magnitude lower than the values found by MT19 (∼10 mm) and WX23 (∼12 mm), with no overlap between our confidence intervals (Figure 3b). Despite this, we find strong agreement with their estimates of sea level mitigation from WAIS (∼2–3 mm) and AP (∼0 mm). Thus, the discrepancy comes from EAIS. Both MT19 and WX23 find EAIS to have dominated (∼8 mm) the overall AIS mitigation contribution, while we find the contribution of EAIS to be insignificant (Figure 3b). This discrepancy stems from different estimates of the 19th-century baseline used to calculate 20th-century mitigation, which we discuss in the following section.

Table 1
Cumulative Estimates and Trends in 20th-Century Sea Level Mitigation for Each Antarctic Sector, With Uncertainties Representing the 95% Confidence Interval

	Cumulative mitigation: 1901–2000 (mm)	Mitigation trend: 1901–1970 (mm dec^{-1})	Mitigation trend: 1970–2000 (mm dec^{-1})
West Antarctic Ice Sheet	**1.71 ± 0.99**	0.09 ± 0.10	**0.34 ± 0.10**
East Antarctic Ice Sheet	−0.27 ± 1.88	−0.13 ± 0.13	**0.31 ± 0.13**
Antarctic Peninsula	−0.20 ± 0.48	**−0.06 ± 0.02**	**0.07 ± 0.02**
Antarctic Ice Sheet	1.24 ± 3.47	−0.11 ± 0.26	**0.72 ± 0.26**

Note. Significant values and trends are bolded.

4. Discussion

4.1. Source of Disagreement With Previous Mitigation Estimates

To our knowledge, only two previous Antarctic accumulation reconstructions (MT19 and WX23) have quantified the equivalent impact on sea level rise; both of these studies utilize similar methodologies, following Monaghan et al. (2006). Our estimate of 20th-century sea level mitigation (∼1 mm) is substantially smaller than that of MT19 (∼10 mm) and WX23 (∼12 mm). Nevertheless, we agree with both reconstructions on numerous points: (a) a significant 1901–2000 AIS accumulation increase (∼0.4–0.6 Gt yr^{-2}); (b) similar 20th-century spatial trends, including a positive trend in AP and eastern WAIS, and a negative trend in western WAIS (Figures 2e–2g); and (c) similar 1901–2000 sea level mitigation from WAIS (∼2–3 mm) and AP (∼0 mm). Thus, the large discrepancy in 20th-century sea level mitigation comes from EAIS.

All three reconstructions find an insignificant 1901–2000 EAIS accumulation trend (∼0.0–0.1 Gt yr^{-2}), despite the disagreement over 20th-century EAIS sea level mitigation. The discrepancy between our reconstruction and those of MT19 and WX23 is instead due to different 19th-century baseline values used to calculate 20th-century mitigation. All three studies obtain a baseline value by taking the 19th-century mean of their own accumulation reconstruction; sea level mitigation is calculated by integrating the 20th-century accumulation time series relative to this value. While we find no significant EAIS accumulation trend from 1801 to 1900, both MT19 and WX23 find a significant accumulation increase during this period. Relative to the 20th-century time series, our 19th-century baseline is higher. If we decrease our baseline value to match that of MT19 (by 29 Gt yr^{-1}), we obtain 20th-century mitigation values (AIS: 9.2 ± 3.5 mm; EAIS: 7.7 ± 1.9 mm) that agree closely with MT19 and WX23. Thus, the observed disagreement is dominated by uncertainty in 19th-century EAIS accumulation.

Both MT19 and WX23 use the kriging-like interpolation method of Monaghan et al. (2006) to generate spatially complete estimates of past accumulation trend. Agreement between the two reconstructions is therefore unsurprising. Their disagreement with our reconstruction over the 19th-century EAIS trend is due to methodological differences, as we all use a similar proxy network. Where proxy records for a given spatial region have high variance and disagree with one another, as is the case across EAIS (Thomas et al., 2017), our reconstruction will default to no trend. By contrast, the method of MT19 and WX23 relies on extrapolation of satellite-era (1979–2016) covariance between proxy records and climate indices, assuming that observed relationships during a period of increasing Antarctic accumulation are constant.

Our data assimilation-based reconstruction contributes methodological diversity to the limited set of 20th-century Antarctic sea level mitigation estimates. Both our and previous approaches demonstrate skill in WAIS, where a high-quality, spatially well-distributed proxy network is available; neither method demonstrates significant skill in EAIS. Thus, the disagreement in 19th-century AIS accumulation is due to uncertainties in the EAIS proxy record, which is highly variable, geographically sparse, and agrees poorly with external climate estimates (Thomas et al., 2017). The lack of overlapping EAIS uncertainties between our reconstruction and MT19 suggests that both approaches underestimate the true uncertainty of accumulation histories in data-sparse regions. This lack of skill in EAIS precludes a confident estimate of total 20th-century sea level mitigation from AIS.

4.2. Late 20th-Century Mitigation and Comparison With Dynamic Ice Loss

We find significant AIS-wide sea level mitigation from 1970 onwards (Table 1). The decadal trend in sea level mitigation shows a consistent increase after 1960, ultimately becoming positive (95% confidence) from 1970 onwards. This late 20th-century trend reflects a significant mitigation of sea level rise, distinct from the previous 160 years of the reconstruction. While MT19 find AIS to mitigate sea level rise throughout the 20th-century, they note a doubling of the mitigation rate after 1979. Indeed, the accelerating overall AIS accumulation trend (Figure 2a) suggests that the AIS continued to mitigate sea level rise into the 21st-century; this is supported by instrumental reanalyzes, including ERA5 and MERRA-2 (Gelaro et al., 2017), which show a positive Antarctic precipitation trend from the late 20th-century into the present. Increasing snow accumulation over WAIS since the late 20th-century has been attributed to anthropogenic causes (Dalaiden et al., 2022), and increased snow accumulation on the AIS will likely continue to mitigate sea level rise into the future (e.g., Lenaerts et al., 2016).

We note strong spatial similarities between our 1957–2000 reconstruction (Figure 2g) and the 1957–2000 reconstruction of MT19, where the Southern Annular Mode (SAM)-congruent *P* - *E* trend is the dominant principal component (see Figure 1d of Medley and Thomas (2019)); these include a "see-saw" pattern over WAIS, a positive trend over AP, and a negative trend over coastal DML. Medley and Thomas (2019) determine that spatial accumulation variability is dominated by dynamic change, in the form of an anthropogenically forced (Arblaster & Meehl, 2006; Fogt & Marshall, 2020) positive trend in the SAM. Our results are consistent with this finding. Furthermore, existing SAM reconstructions (King et al., 2023; O'Connor et al., 2021) have found the modern anthropogenically driven trend to begin in the mid-to-late 20th-century, occurring near-contemporaneously with the positive accumulation trend in our reconstruction.

While AIS accumulation mitigated sea level rise during the late 20th-century, this assessment does not account for contemporaneous mass loss. We find that increasing accumulation mitigated 59% of the sea level rise caused by dynamic ice loss from 1979 to 1999 (Rignot et al., 2019). From 1979 to 1989, we find cumulative mass gain of 36 ± 9 Gt yr^{-1}; for the same period, Rignot et al. (2019) find mass loss of 52 ± 7 Gt yr^{-1}. Likewise, from 1989 to 1999, we find mass gain to increase by 41 ± 9 Gt yr^{-1}, while Rignot et al. (2019) find mass loss to increase by 79 ± 11 Gt yr^{-1}. The regions with the greatest increases in accumulation, such as AP and Amundsen Sea Coast, were those that saw the greatest increases in dynamic ice loss (Gardner et al., 2018). While increased accumulation directly mitigates sea level rise through ice sheet mass gain, it can also indirectly raise sea level by enhancing ice dynamic flux (Frieler et al., 2015), although modern dynamic ice loss appears driven by oceanic forcing of outlet glaciers (Smith et al., 2020). While Antarctic accumulation had a mitigating effect on the contribution to sea level rise, it likely did not keep pace with contemporaneous late 20th-century mass loss.

4.3. Outlook

Numerous limitations in the proxy record impede our understanding of past EAIS accumulation. Spatial and temporal proxy coverage is sparse: the majority of records are located in a limited area around central DML (Figure S1 in Supporting Information S1), and many records do not span the full reconstruction period (Figure S2 in Supporting Information S1). Furthermore, low accumulation rates across much of EAIS preclude accurate identification of annual layers, leading to lower-quality records. Thomas et al. (2017) conclude that existing records from the East Antarctic Plateau may not be representative of true regional trends, as the regional ice core composite shows poor agreement with modeled SMB from RACMO2 (van Wessem et al., 2018).

EAIS is the dominant contributor to Antarctic accumulation, accounting for approximately 70% of net annual accumulation over AIS (Mottram et al., 2021). Thus, uncertainty in EAIS accumulation has significant implications for future sea level change. Antarctic sea level projections for the 21st-century consistently show a regional disparity, with WAIS losing mass and EAIS gaining mass; EAIS is thus predicted to be a principal mitigator of future sea level rise (Payne et al., 2021; Seroussi et al., 2020; Siahaan et al., 2022). However, observational estimates of Antarctic mass change have indicated substantial uncertainty around the EAIS contribution, in part due to short and varying observational timescales. Shepherd et al. (2018) find an insignificant EAIS mass gain trend of 5 ± 46 Gt yr^{-1} from 1992 to 2017; alternate studies have found EAIS to be either gaining (Smith et al., 2020; Zwally et al., 2015) or losing (Rignot et al., 2019) mass.

The large disagreement between our EAIS reconstruction and those of MT19 and WX23, all of which use similar input data and dynamically consistent spatial interpolation methods, highlights the need for better constraints on EAIS accumulation history and climate sensitivity, as well as improvements in methodology. To gain a better understanding of temporal trends in EAIS accumulation, greater spatial diversity of EAIS ice core sites is necessary. In particular, we note the high uncertainty in our reconstruction around Wilkes Land (Figure S5 in Supporting Information S1), likely due to a dearth of existing ice cores (Figure S1 in Supporting Information S1). An investigation of optimal EAIS drilling sites (Vance et al., 2016) identified specific locations where high-resolution records, geographically complementary to existing sites, can likely be obtained. As ice core records yield information for a large geographic area, higher accumulation coastal cores can provide insight into the low accumulation-rate interior. To address the 19th-century baseline issue, high-frequency ice penetrating radar, which images the upper ~100 m, can be used to infer multi-decadal accumulation rates (e.g., Le Meur et al., 2018), with greatly improved spatial coverage compared to ice cores. Extending ice cores to the present would allow analysis that is contemporaneous with satellite observations of Antarctic mass change (e.g., Shepherd et al., 2018; Smith et al., 2020). Higher quality temperature and accumulation histories, and a data assimilation approach that does not rely on the temperature-accumulation relationship, are also necessary to assess the sensitivity of accumulation to temperature change (e.g., Nicola et al., 2023). Direct assimilation of accumulation records (e.g., Dalaiden et al., 2021) has the advantage of being independent of biases in temperature-accumulation sensitivity but also has a variety of challenges that lead to lower skill, particularly in East Antarctica (Text S5 in Supporting Information S1; Table S2 in Supporting Information S1). Understanding the relative strengths of reconstructions using both the temperature-accumulation relationship and direct assimilation will be an important extension of our current work. While internally consistent estimation of the error covariance matrix is a notable challenge, it can be estimated by quantifying the spatial representativeness of ice core accumulation records and would open up significant opportunities to examine the temperature-accumulation relationship over time (e.g., Badgeley et al., 2020). Moreover, additional records will help constrain the sensitivity of Antarctic accumulation to future warming and the amount of sea level mitigation.

5. Conclusion

We employ a paleoclimate data assimilation methodology to integrate ice core records with climate model simulations, thereby producing an annually resolved reconstruction of Antarctic snow accumulation from 1801 to 2000 CE. We demonstrate good reconstruction skill in WAIS and AP where a high-quality array of ice core records exists; in EAIS, the reconstruction skill is not significant, likely due to the sparsity of high-quality ice core records. We find that Antarctic accumulation rates increased in the 20th-century, primarily driven by a late-century acceleration in West Antarctica. We find modest sea level mitigation of ∼1 mm in the 20th-century, which contrasts with the much larger estimates of ∼10–12 mm found by Medley and Thomas (2019) and Wang and Xiao (2023). As all three studies agree on mitigation from WAIS and AP, the discrepancy is dominated by different estimates of mean 19th-century accumulation in EAIS. Our results suggest that uncertainty in 20th-century Antarctic sea level mitigation is substantial, indicating the need for better constraints on East Antarctic accumulation history and climate sensitivity. Additional ice cores, selected for high accumulation rates to preserve robust annual variation and with a targeted spatial distribution, would allow for more confident reconstruction and would place firmer constraints on future changes in sea level.

Data Availability Statement

Our archived reconstructions can be found in (Eswaran et al., 2023). To produce reconstructions, we use the Last Millennium Reanalysis data assimilation framework, which is open-sourced on GitHub (Hakim, 2016). Ice core proxy data is primarily compiled in PAGES 2k consortium databases: we use both water isotope and accumulation records (Stenni, 2017; E. Thomas, 2017). We additionally incorporate individual ice core records from the South Pole ice core (Kahle et al., 2021), Derwael Ice Rise (Philippe et al., 2016), and the PIG2010, DIV2010, and THW2010 sites (Criscitiello et al., 2013). To construct the climate model priors, we use CMIP5 Last Millennium output from CCSM4 (Gent et al., 2011), iCESM (Brady et al., 2019), BCC-CSM1.1 (Wu et al., 2014), CSIRO Mk3L (Phipps et al., 2012), FGOALS-s2 (Bao et al., 2013), GISS-E2-R (Schmidt et al., 2014), HadCM3 (Collins et al., 2001), IPSL-CM5A-LR (Dufresne et al., 2013), and MPI-ESM (Gutjahr et al., 2019). The proxy calibration data set used is the GISS Surface Temperature Analysis (Hansen et al., 2010). We additionally utilize reanalysis data from ERA5 (Hersbach et al., 2020) and MERRA-2 (Gelaro et al., 2017).

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References

Arblaster, J. M., & Meehl, G. A. (2006). Contributions of external forcings to southern annular mode trends. *Journal of Climate*, *19*(12), 2896–2905. https://doi.org/10.1175/JCLI3774.1

Badgeley, J. A., Steig, E. J., Hakim, G. J., & Fudge, T. J. (2020). Greenland temperature and precipitation over the last 20,000 years using data assimilation. *Climate of the Past*, *16*(4), 1325–1346. https://doi.org/10.5194/cp-16-1325-2020

Bao, Q., Lin, P., Zhou, T., Liu, Y., Yu, Y., Wu, G., et al. (2013). The flexible global ocean-atmosphere-land system model, spectral version 2: FGOALS-s2 [Dataset]. *Advances in Atmospheric Sciences*, *30*, 561–576. https://doi.org/10.1007/s00376-012-2113-9

Brady, E., Stevenson, S., Bailey, D., Liu, Z., Noone, D., Nusbaumer, J., et al. (2019). The connected isotopic water cycle in the Community Earth System Model version 1 [Dataset]. *Journal of Advances in Modeling Earth Systems*, *11*(8), 2547–2566. https://doi.org/10.1029/2019MS001663

Collins, M., Tett, S. F. B., & Cooper, C. (2001). The internal climate variability of HadCM3, a version of the Hadley Centre coupled model without flux adjustments [Dataset]. *Climate Dynamics*, *17*, 61–81. https://doi.org/10.1007/s003820000094

Criscitiello, A. S., Das, S. B., Evans, M. J., Frey, K. E., Conway, H., Joughin, I., et al. (2013). Ice sheet record of recent sea-ice behavior and polynya variability in the Amundsen Sea, West Antarctica [Dataset]. *Journal of Geophysical Research: Oceans*, *118*(1), 118–130. https://doi.org/10.1029/2012JC008077

Dalaiden, Q., Goosse, H., Klein, F., Lenaerts, J. T. M., Holloway, M., Sime, L., & Thomas, E. R. (2020). How useful is snow accumulation in reconstructing surface air temperature in Antarctica? A study combining ice core records and climate models. *The Cryosphere*, *14*(4), 1187–1207. https://doi.org/10.5194/tc-14-1187-2020

Dalaiden, Q., Goosse, H., Rezsöhazy, J., & Thomas, E. R. (2021). Reconstructing atmospheric circulation and sea-ice extent in the West Antarctic over the past 200 years using data assimilation. *Climate Dynamics*, *57*(11), 3479–3503. https://doi.org/10.1007/s00382-021-05879-6

Dalaiden, Q., Schurer, A. P., Kirchmeier-Young, M. C., Goosse, H., & Hegerl, G. C. (2022). West Antarctic surface climate changes since the mid-20th century driven by anthropogenic forcing. *Geophysical Research Letters*, *49*(16), e2022GL099543. https://doi.org/10.1029/2022GL099543

Dufresne, J.-L., Foujols, M.-A., Denvil, S., Caubel, A., Marti, O., Aumont, O., et al. (2013). Climate change projections using the IPSL-CM5 Earth System Model: From CMIP3 to CMIP5 [Dataset]. *Climate Dynamics*, *40*, 2123–2165. https://doi.org/10.1007/s00382-012-1636-1

Edwards, T. L., Nowicki, S., Marzeion, B., Hock, R., Goelzer, H., Seroussi, H., et al. (2021). Projected land ice contributions to twenty-first-century sea level rise. *Nature*, *593*(7857), 74–82. https://doi.org/10.1038/s41586-021-03302-y

Eswaran, A., Truax, O., & Fudge, T. J. (2023). Reconstruction of Antarctic accumulation from 1801-2000 CE [Dataset]. *Zenodo*. https://doi.org/10.5281/zenodo.10030668

Fogt, R. L., & Marshall, G. J. (2020). The Southern Annular Mode: Variability, trends, and climate impacts across the Southern Hemisphere. *WIREs Climate Change*, *11*(4), e652. https://doi.org/10.1002/wcc.652

Frezzotti, M., Scarchilli, C., Becagli, S., Proposito, M., & Urbini, S. (2013). A synthesis of the Antarctic surface mass balance during the last 800 yr. *The Cryosphere*, *7*(1), 303–319. https://doi.org/10.5194/tc-7-303-2013

Frieler, K., Clark, P. U., He, F., Buizert, C., Reese, R., Ligtenberg, S. R. M., et al. (2015). Consistent evidence of increasing Antarctic accumulation with warming. *Nature Climate Change*, *5*(4), 348–352. https://doi.org/10.1038/nclimate2574

Fudge, T. J., Markle, B. R., Cuffey, K. M., Buizert, C., Taylor, K. C., Steig, E. J., et al. (2016). Variable relationship between accumulation and temperature in West Antarctica for the past 31,000 years. *Geophysical Research Letters*, *43*(8), 3795–3803. https://doi.org/10.1002/2016GL068356

Gardner, A. S., Moholdt, G., Scambos, T., Fahnstock, M., Ligtenberg, S., van den Broeke, M., & Nilsson, J. (2018). Increased West Antarctic and unchanged East Antarctic ice discharge over the last 7 years. *The Cryosphere*, *12*(2), 521–547. https://doi.org/10.5194/tc-12-521-2018

Gelaro, R., McCarty, W., Suárez, M. J., Todling, R., Molod, A., Takacs, L., et al. (2017). The modern-era retrospective analysis for Research and applications, version 2 (MERRA-2) [Dataset]. *Journal of Climate*, *30*, 5419–5454. https://doi.org/10.1175/JCLI-D-16-0758.1

Gent, P. R., Danabasoglu, G., Donner, L. J., Holland, M. M., Hunke, E. C., Jayne, S. R., et al. (2011). The community climate system model version 4 [Dataset]. *Journal of Climate*, *24*(19), 4973–4991. https://doi.org/10.1175/2011JCLI4083.1

Golledge, N. R., Keller, E. D., Gomez, N., Naughten, K. A., Bernales, J., Trusel, L. D., & Edwards, T. L. (2019). Global environmental consequences of twenty-first-century ice-sheet melt. *Nature*, *566*(7742), 65. https://doi.org/10.1038/s41586-019-0889-9

Gutjahr, O., Putrasahan, D., Lohmann, K., Jungclaus, J. H., von Storch, J.-S., Brüggemann, N., et al. (2019). Max planck institute Earth system model (MPI-ESM1.2) for the high-resolution model intercomparison project (HighResMIP). [Dataset]. *Geoscientific Model Development*, *12*(7), 3241–3281. https://doi.org/10.5194/gmd-12-3241-2019

Hakim, G. (2016). Last millennium reanalysis [Python] [Software]. *GitHub*. https://github.com/modons/LMR

Hakim, G. J., Emile-Geay, J., Steig, E. J., Noone, D., Anderson, D. M., Tardif, R., et al. (2016). The last millennium climate reanalysis project: Framework and first results. *Journal of Geophysical Research: Atmospheres*, *121*(12), 6745–6764. https://doi.org/10.1002/2016JD024751

Hansen, J., Ruedy, R., Sato, M., & Lo, K. (2010). Global surface temperature change [Dataset]. *Reviews of Geophysics*, *48*(4), RG4004. https://doi.org/10.1029/2010RG000345

Hersbach, H., Bell, B., Berrisford, P., Hirahara, S., Horányi, A., Muñoz-Sabater, J., et al. (2020). The ERA5 global reanalysis [Dataset]. *Quarterly Journal of the Royal Meteorological Society*, *146*(730), 1999–2049. https://doi.org/10.1002/qj.3803

Kahle, E. C., Steig, E. J., Jones, T. R., Fudge, T. J., Koutnik, M. R., Morris, V. A., et al. (2021). Reconstruction of temperature, accumulation rate, and layer thinning from an ice core at South Pole, using a statistical inverse method [Dataset]. *Journal of Geophysical Research: Atmospheres*, *126*(13), e2020JD033300. https://doi.org/10.1029/2020JD033300

King, J., Anchukaitis, K. J., Allen, K., Vance, T., & Hessl, A. (2023). Trends and variability in the Southern Annular Mode over the Common Era. *Nature Communications*, *14*(1), 2324. https://doi.org/10.1038/s41467-023-37643-1

Klein, F., Abram, N. J., Curran, M. A. J., Goosse, H., Goursaud, S., Masson-Delmotte, V., et al. (2019). Assessing the robustness of Antarctic temperature reconstructions over the past 2 millennia using pseudoproxy and data assimilation experiments. *Climate of the Past*, *15*(2), 661–684. https://doi.org/10.5194/cp-15-661-2019

Le Meur, E., Magand, O., Arnaud, L., Fily, M., Frezzotti, M., Cavitte, M., et al. (2018). Spatial and temporal distributions of surface mass balance between Concordia and Vostok stations, Antarctica, from combined radar and ice core data: First results and detailed error analysis. *The Cryosphere*, *12*(5), 1831–1850. https://doi.org/10.5194/tc-12-1831-2018

Lenaerts, J. T. M., Vizcaino, M., Fyke, J., van Kampenhout, L., & van den Broeke, M. R. (2016). Present-day and future Antarctic ice sheet climate and surface mass balance in the Community Earth System Model. *Climate Dynamics*, *47*(5), 1367–1381. https://doi.org/10.1007/s00382-015-2907-4

Levermann, A., Winkelmann, R., Albrecht, T., Goelzer, H., Golledge, N. R., Greve, R., et al. (2020). Projecting Antarctica's contribution to future sea level rise from basal ice shelf melt using linear response functions of 16 ice sheet models (LARMIP-2). *Earth System Dynamics*, *11*(1), 35–76. https://doi.org/10.5194/esd-11-35-2020

Medley, B., & Thomas, E. R. (2019). Increased snowfall over the Antarctic Ice Sheet mitigated twentieth-century sea-level rise. *Nature Climate Change*, *9*(1), 34–39. https://doi.org/10.1038/s41558-018-0356-x

Monaghan, A. J., Bromwich, D. H., Fogt, R. L., Wang, S.-H., Mayewski, P. A., Dixon, D. A., et al. (2006). Insignificant change in Antarctic snowfall since the international Geophysical Year. *Science*, *313*(5788), 827–831. https://doi.org/10.1126/science.1128243

Mottram, R., Hansen, N., Kittel, C., van Wessem, J. M., Agosta, C., Amory, C., et al. (2021). What is the surface mass balance of Antarctica? An intercomparison of regional climate model estimates. *The Cryosphere*, *15*(8), 3751–3784. https://doi.org/10.5194/tc-15-3751-2021

Nash, J. E., & Sutcliffe, J. V. (1970). River flow forecasting through conceptual models part I—A discussion of principles. *Journal of Hydrology*, *10*(3), 282–290. https://doi.org/10.1016/0022-1694(70)90255-6

Nicola, L., Notz, D., & Winkelmann, R. (2023). Revisiting temperature sensitivity: How does Antarctic precipitation change with temperature? *The Cryosphere*, *17*(7), 2563–2583. https://doi.org/10.5194/tc-17-2563-2023

Nicolas, J. P., & Bromwich, D. H. (2014). New reconstruction of Antarctic near-surface temperatures: Multidecadal trends and reliability of global reanalyses. *Journal of Climate*, *27*(21), 8070–8093. https://doi.org/10.1175/JCLI-D-13-00733.1

O'Connor, G. K., Steig, E. J., & Hakim, G. J. (2021). Strengthening Southern Hemisphere westerlies and Amundsen Sea low deepening over the 20th century revealed by proxy-data assimilation. *Geophysical Research Letters*, *48*(24), e2021GL095999. https://doi.org/10.1029/2021GL095999

Parsons, L. A., Amrhein, D. E., Sanchez, S. C., Tardif, R., Brennan, M. K., & Hakim, G. J. (2021). Do multi-model ensembles improve reconstruction skill in paleoclimate data assimilation? *Earth and Space Science*, *8*(4), e2020EA001467. https://doi.org/10.1029/2020EA001467

Payne, A. J., Nowicki, S., Abe-Ouchi, A., Agosta, C., Alexander, P., Albrecht, T., et al. (2021). Future sea level change under coupled model intercomparison project phase 5 and phase 6 scenarios from the Greenland and Antarctic ice sheets. *Geophysical Research Letters*, *48*(16), e2020GL091741. https://doi.org/10.1029/2020GL091741

Philippe, M., Tison, J.-L., Fjøsne, K., Hubbard, B., Kjær, H. A., Lenaerts, J. T. M., et al. (2016). Ice core evidence for a 20th century increase in surface mass balance in coastal Dronning Maud Land, East Antarctica [Dataset]. *The Cryosphere*, *10*(5), 2501–2516. https://doi.org/10.5194/tc-10-2501-2016

Phipps, S. J., Rotstayn, L. D., Gordon, H. B., Roberts, J. L., Hirst, A. C., & Budd, W. F. (2012). The CSIRO Mk3L climate system model version 1.0–Part 2: Response to external forcings [Dataset]. *Geoscientific Model Development*, *5*(3), 649–682. https://doi.org/10.5194/gmd-5-649-2012

Pritchard, H. D., Arthern, R. J., Vaughan, D. G., & Edwards, L. A. (2009). Extensive dynamic thinning on the margins of the Greenland and Antarctic ice sheets. *Nature*, *461*(7266), 971–975. https://doi.org/10.1038/nature08471

Rignot, E., Mouginot, J., Scheuchl, B., van den Broeke, M., van Wessem, M. J., & Morlighem, M. (2019). Four decades of Antarctic ice sheet mass balance from 1979–2017. *Proceedings of the National Academy of Sciences*, *116*(4), 1095–1103. https://doi.org/10.1073/pnas.1812883116

Schmidt, G. A., Kelley, M., Nazarenko, L., Ruedy, R., Russell, G. L., Aleinov, I., et al. (2014). Configuration and assessment of the GISS ModelE2 contributions to the CMIP5 archive [Dataset]. *Journal of Advances in Modeling Earth Systems*, *6*(1), 141–184. https://doi.org/10.1002/2013MS000265

Schneider, D. P., & Fogt, R. L. (2018). Artifacts in century-length atmospheric and coupled reanalyses over Antarctica due to historical data availability. *Geophysical Research Letters*, *45*(2), 964–973. https://doi.org/10.1002/2017GL076226

Seroussi, H., Nowicki, S., Payne, A. J., Goelzer, H., Lipscomb, W. H., Abe-Ouchi, A., et al. (2020). ISMIP6 Antarctica: A multi-model ensemble of the Antarctic ice sheet evolution over the 21st century. *The Cryosphere*, *14*(9), 3033–3070. https://doi.org/10.5194/tc-14-3033-2020

Shepherd, A., Ivins, E., Rignot, E., Smith, B., van den Broeke, M., Velicogna, I., et al. (2018). Mass balance of the Antarctic ice sheet from 1992 to 2017. *Nature*, *558*(7709), 219–222. https://doi.org/10.1038/s41586-018-0179-y

Siahaan, A., Smith, R. S., Holland, P. R., Jenkins, A., Gregory, J. M., Lee, V., et al. (2022). The Antarctic contribution to 21st-century sea-level rise predicted by the UK Earth System Model with an interactive ice sheet. *The Cryosphere*, *16*(10), 4053–4086. https://doi.org/10.5194/tc-16-4053-2022

Smith, B., Fricker, H. A., Gardner, A. S., Medley, B., Nilsson, J., Paolo, F. S., et al. (2020). Pervasive ice sheet mass loss reflects competing ocean and atmosphere processes. *Science*, *368*(6496), 1239–1242. https://doi.org/10.1126/science.aaz5845

Steig, E. J., Schneider, D. P., Rutherford, S. D., Mann, M. E., Comiso, J. C., & Shindell, D. T. (2009). Warming of the Antarctic ice-sheet surface since the 1957 International Geophysical Year. *Nature*, *457*(7228), 459–462. https://doi.org/10.1038/nature07669

Steiger, N. J., Steig, E. J., Dee, S. G., Roe, G. H., & Hakim, G. J. (2017). Climate reconstruction using data assimilation of water isotope ratios from ice cores. *Journal of Geophysical Research: Atmospheres*, *122*(3), 1545–1568. https://doi.org/10.1002/2016JD026011

Stenni, B. (2017). PAGES Antarctica2k temperature reconstructions [Dataset]. *National Centers for Environmental Information*, https://doi.org/10.25921/h6nr-kt92

Stenni, B., Curran, M. A. J., Abram, N. J., Orsi, A., Goursaud, S., Masson-Delmotte, V., et al. (2017). Antarctic climate variability on regional and continental scales over the last 2000 years. *Climate of the Past*, *13*(11), 1609–1634. https://doi.org/10.5194/cp-13-1609-2017

Tardif, R., Hakim, G. J., Perkins, W. A., Horlick, K. A., Erb, M. P., Emile-Geay, J., et al. (2019). Last Millennium Reanalysis with an expanded proxy database and seasonal proxy modeling. *Climate of the Past*, *15*(4), 1251–1273. https://doi.org/10.5194/cp-15-1251-2019

Taylor, K. E., Stouffer, R. J., & Meehl, G. A. (2012). An overview of CMIP5 and the experiment design. *Bulletin of the American Meteorological Society*, *93*(4), 485–498. https://doi.org/10.1175/BAMS-D-11-00094.1

Thomas, E. (2017). Antarctic regional snow accumulation composites over the past 1000 years [Dataset]. *British Antarctic Survey*, https://doi.org/10.5285/cc1d42de-dfe6-40aa-a1a6-d45cb2fc8293

Thomas, E. R., van Wessem, J. M., Roberts, J., Isaksson, E., Schlosser, E., Fudge, T. J., et al. (2017). Regional Antarctic snow accumulation over the past 1000 years. *Climate of the Past*, *13*(11), 1491–1513. https://doi.org/10.5194/cp-13-1491-2017

Vance, T. R., Roberts, J. L., Moy, A. D., Curran, M. A. J., Tozer, C. R., Gallant, A. J. E., et al. (2016). Optimal site selection for a high-resolution ice core record in East Antarctica. *Climate of the Past*, *12*(3), 595–610. https://doi.org/10.5194/cp-12-595-2016

van Wessem, J. M., van de Berg, W. J., Noël, B. P. Y., van Meijgaard, E., Amory, C., Birnbaum, G., et al. (2018). Modelling the climate and surface mass balance of polar ice sheets using RACMO2 – Part 2: Antarctica (1979–2016). *The Cryosphere*, *12*(4), 1479–1498. https://doi.org/10.5194/tc-12-1479-2018

Wang, Y., & Xiao, C. (2023). An increase in the Antarctic surface mass balance during the past three centuries, dampening global Sea Level rise. *Journal of Climate*, *36*(23), 8127–8138. https://doi.org/10.1175/JCLI-D-22-0747.1

Wu, T., Song, L., Li, W., Wang, Z., Zhang, H., Xin, X., et al. (2014). An overview of BCC climate system model development and application for climate change studies [Dataset]. *Journal of Meteorological Research*, *28*, 34–56. https://doi.org/10.1007/s13351-014-3041-7

Zwally, H. J., Giovinetto, M. B., Beckley, M. A., & Saba, J. L. (2012). *Antarctic and Greenland drainage systems*. GSFC Cryospheric Sciences Laboratory.

Zwally, H. J., Li, J., Robbins, J. W., Saba, J. L., Yi, D., & Brenner, A. C. (2015). Mass gains of the Antarctic ice sheet exceed losses. *Journal of Glaciology*, *61*(230), 1019–1036. https://doi.org/10.3189/2015JoG15J071