Positive Late 20th-century Trend in Antarctic Snow Accumulation Drives Modest Mitigation of Sea Level Rise

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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 mm 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

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 a previous mitigation estimate of ~10 mm; this discrepancy is due to unconstrained 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 and a negative contribution (lowering sea level) from increased snow accumulation. In response to warming temperatures over Antarctica, both ice-shelf basal melting (Golledge et al., 2019; Levermann et al., 2020) and snow accumulation (Kittel et al., 2021; Lenaerts et al., 2016) are projected to increase. However, studies of the Antarctic temperature-accumulation relationship have indicated a wide range in sensitivity (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 in order 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; 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).

Paleoclimate data assimilation is a powerful framework for generating spatially complete climate reconstructions from geographically sparse proxy datasets. Combining both spatial information from climate models and temporal information from proxy records, this approach offers greater versatility than alternate statistical methods, in addition to assuring compatibility with the physics of the climate system and providing 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 reanalyses (Monaghan et al., 2006; Medley & Thomas, 2019) 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 adjust this framework to incorporate a comprehensive 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 1801-2000 CE, and evaluate the skill of resulting reconstructions. Finally, we quantify the effect of reconstructed accumulation trends on the contribution to global mean sea level.

2 Methods

We make use of 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 Supporting Information S4). 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; more details in Supporting Information S2).

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-S2, more details in 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 Supporting Information S3). Finally, we produce the posterior state estimate: a 250-member ensemble of annually resolved gridded accumulation anomalies from 1801-2000. 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); thus, we terminate 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). 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 Supporting Information S5).

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-S4; Table S1). This verifies 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 own reconstruction; higher skill in WAIS likely reflects denser proxy coverage and higher accumulation rates. We further note that the alternate reconstruction of Medley and Thomas (2019; “MT19”) also displays much greater skill in WAIS than EAIS; indeed, their WAIS skill is slightly higher than ours, while their EAIS skill is slightly lower (Table S2).

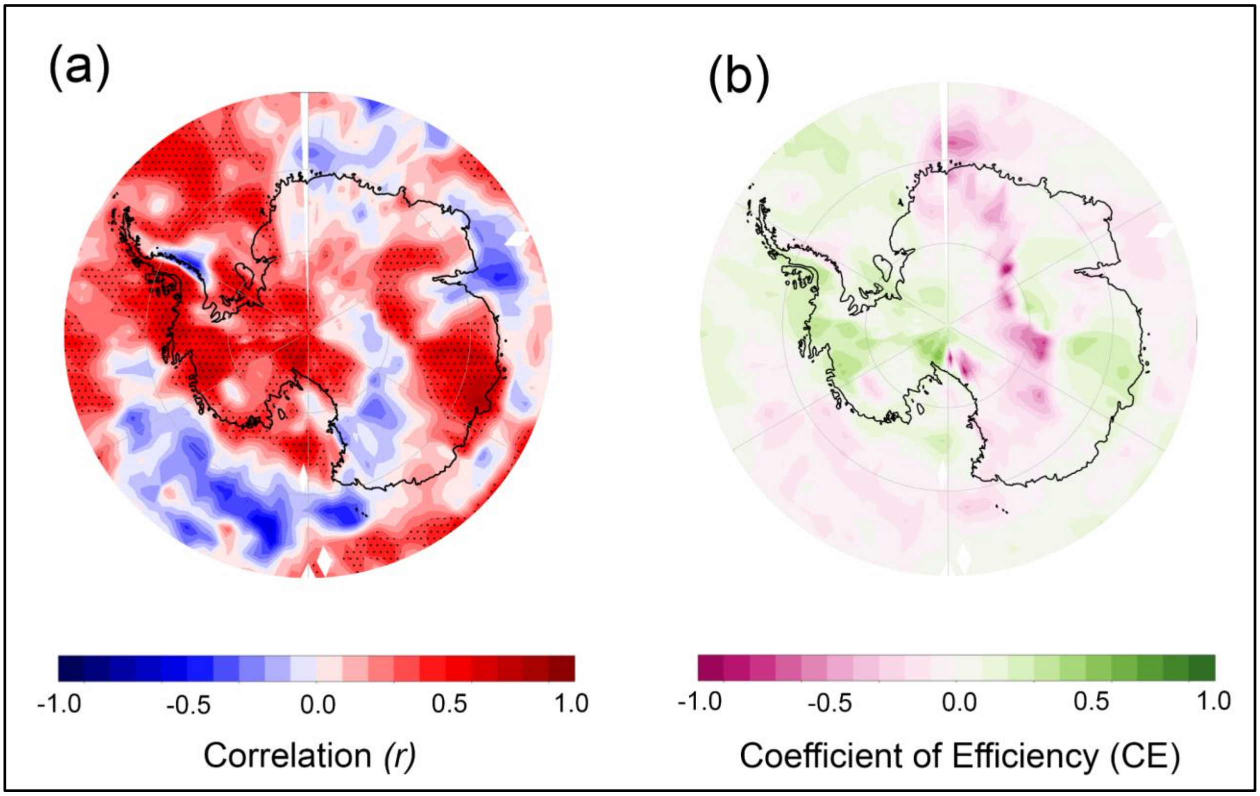

Figure 1: (a) Correlation and (b) coefficient of efficiency between the MME accumulation reconstruction and ERA5 annual precipitation output for the period 1981-2000 CE. Correlation values with $p < 0.05$ are designated with stippling; positive CE values indicate reconstruction skillfulness.

3.2 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 1901-2000, 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 (Figure 2b, Figure 2d). Within WAIS, 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 by MT19.

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 the estimates from Medley and Thomas (2019) and Dalaiden et al. (2020), both of whom find a statistically significant increase in EAIS accumulation from 1801-2000 (Table S3). We find a significant negative trend in EAIS accumulation from 1980 onwards; this trend is also identified by MT19.

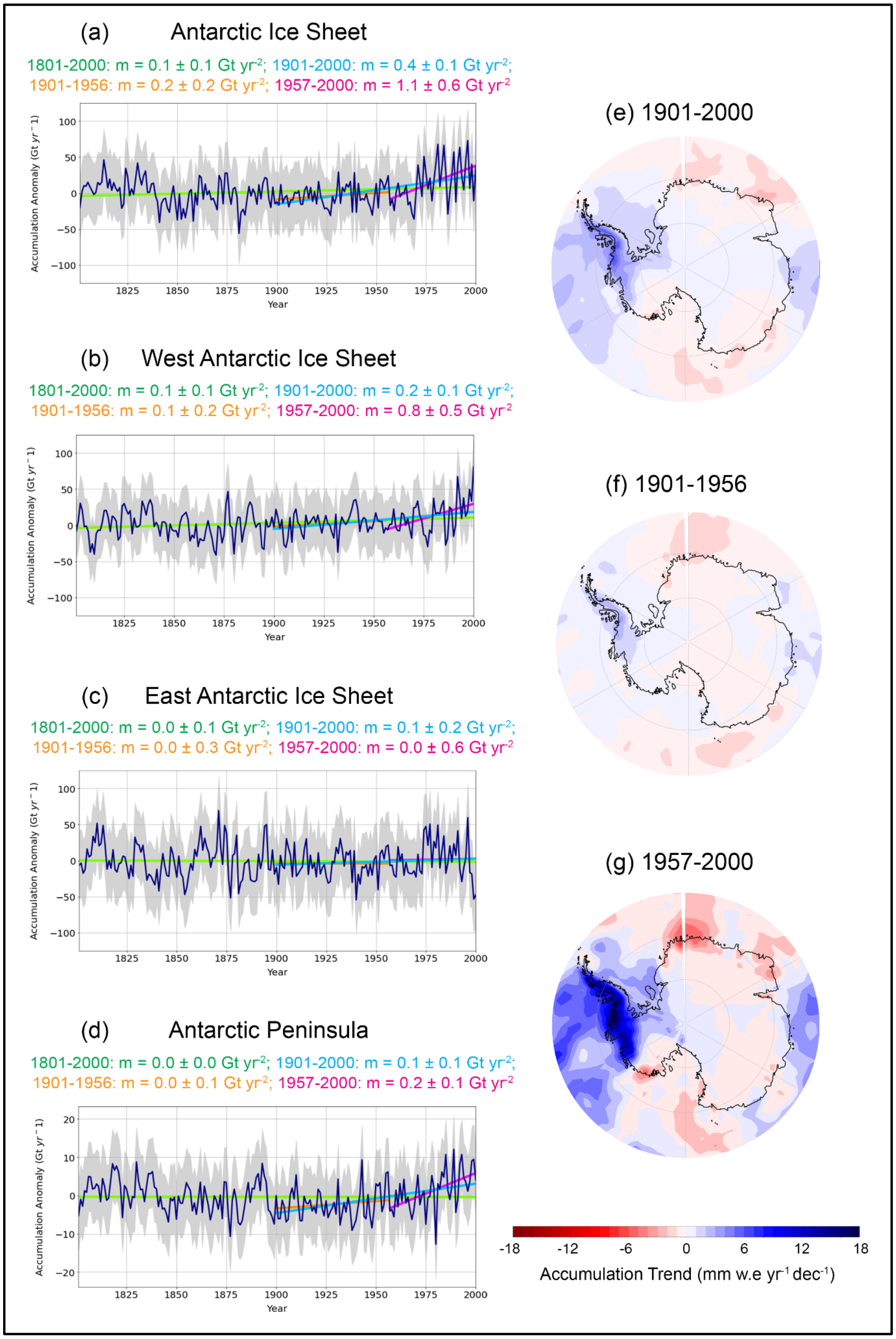

Figure 2: (a-d) Temporal and (e-g) spatial trends in Antarctic accumulation, over the 19th and 20th centuries. Annually resolved accumulation anomalies in (a-d) are shown relative to the 19th-century mean, and represent a spatial integration over the given Antarctic sector. Trendline uncertainties and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

3.3 Sea Level Mitigation

We find that 20th-century AIS sea level mitigation due to snow accumulation (Figure 3a) was insignificant (1.24 ± 3.47 mm), and that WAIS (1.71 ± 0.99 mm) was the only Antarctic sector to definitively mitigate sea level rise (Table 1). We find no significant mitigation from EAIS (-0.27 ± 1.88 mm) or AP (-0.20 ± 0.48 mm).

Examination of a more restricted interval (1970-2000) reveals a significant trend. In our reconstruction, AIS mitigated sea level rise from 1970-2000 (0.72 ± 0.26 mm dec^{-1}, with a total mitigation of 2.16 ± 0.78 mm), comparably driven by both WAIS (0.34 ± 0.10 mm dec^{-1}) and EAIS (0.31 ± 0.13 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 value found by MT19, 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. Medley and Thomas (2019) 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 disagreement over the 19th-century baseline used to calculate 20th-century mitigation, which we discuss in the following section.

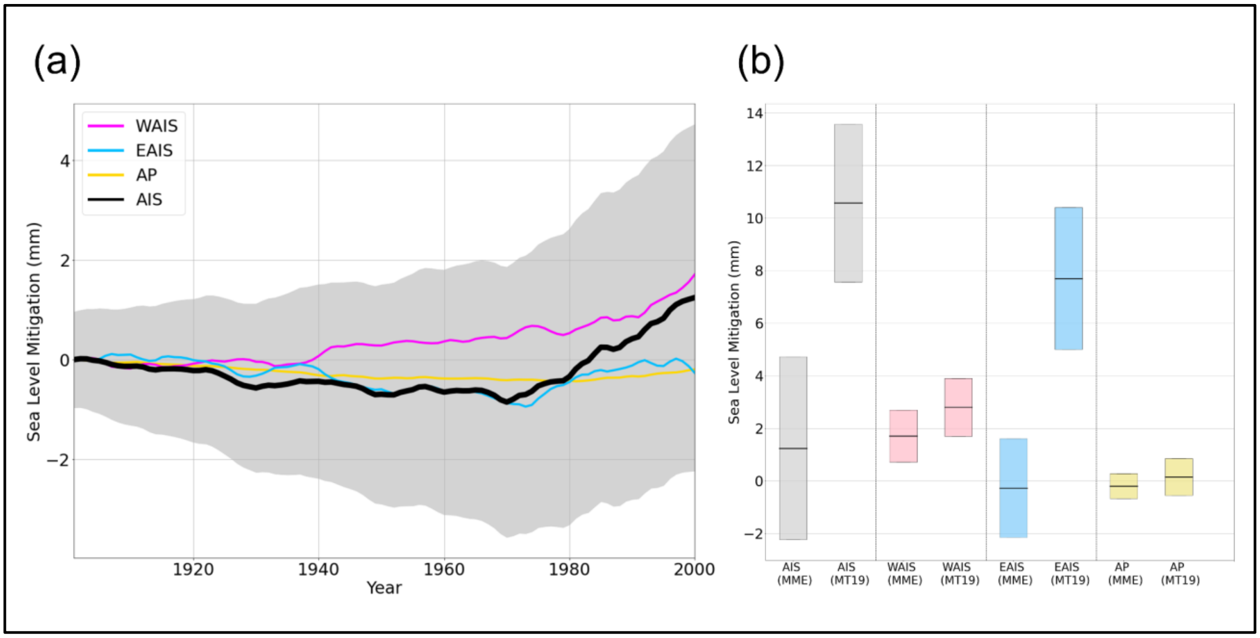

Figure 3: (a) Temporally cumulative sea level mitigation from each Antarctic sector for the period 1901-2000, with the regional 19th-century mean used as the baseline value. Shaded bounds represent the 95% confidence interval for AIS mitigation, accounting for both uncertainty in the 1901-2000 mitigation distribution (±2σ) and the standard error (±2σ_M) of the 19th-century mean. (b) Total 20th-century sea level mitigation for each Antarctic sector, with uncertainties shown; our estimates ("MME") are compared to those from Medley and Thomas (2019; "MT19").

	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**

Table 1: Cumulative estimates and trends in 20th-century sea level mitigation for each Antarctic sector, with uncertainties representing the 95% confidence interval. Significant values and trends are bolded.

4 Discussion

4.1 20th-Century Sea Level Mitigation

We compare our reconstruction with that of MT19. Our estimate of 20th-century sea level mitigation (1.24 ± 3.47 mm) is substantially smaller than their estimate (~10 mm); nevertheless, we find numerous areas of agreement: 1) a similar 1901-2000 AIS-wide annual accumulation trend (0.4 ± 0.1 Gt yr^{-2}) to MT19 (0.6 ± 0.4 Gt yr^{-2}); 2) similar spatial trends, including a dominant positive trend in AP and eastern WAIS, and negative trends in western WAIS and coastal DML (Figures 2e-g); and 3) similar 1901-2000 sea level mitigation from WAIS (~2-3 mm) and AP (~0 mm). Comparison with ERA5 reveals that WAIS and AP exhibited significant reconstruction skill in both studies (Table S2). The large disagreement between our respective 20th-century sea level mitigation estimates is due to EAIS (Figure 3b), where neither method shows statistically significant reconstruction skill.

The disagreement over EAIS sea level mitigation can be attributed to different estimates of the 19th-century mean (i.e. the baseline value for determining post-1900 sea level mitigation). We find no significant EAIS accumulation trend from 1801-1900, while MT19 find a significant positive trend. This trend reduces their estimated 19th-century mean relative to ours; our EAIS baseline is approximately 29 Gt yr^{-1} greater. If we decrease our EAIS baseline by 29 Gt yr^{-1}, leaving all other factors constant, we obtain 20th-century mitigation values (AIS: 9.22 ± 3.47 mm; EAIS: 7.70 ± 1.89 mm) that agree closely with MT19.

The regional accumulation ice core composites from Thomas et al. (2017), which are used by both reconstructions, show no clear 19th-century trend across East Antarctica. Thus, the discrepancies between the 19th-century EAIS accumulation trend in our reconstruction and MT19 can be attributed to (1) different spatial covariance patterns between modern-day (1979-2016) reanalysis data and preindustrial (850-1850) climate simulations and (2) the interpolation method used to blend spatial and proxy data. The reanalysis-based interpolation used by MT19 allows for much higher spatial resolution; however, their covariance patterns are from a relatively limited time period, which may be less relevant for the 19th-century. Conversely, our climate simulation-based interpolation has a lower resolution and is sensitive to model-covariance bias; nevertheless, it incorporates a wider set of prior climate states and a validated formal approach to objectively blend proxy and model data. Both approaches demonstrate high reconstruction skill in regions with higher accumulation rates and more proxy sites; however, neither method demonstrates significant skill in EAIS during the observational period. Furthermore, the lack of overlapping EAIS uncertainties suggests that both approaches may 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 reanalyses, including ERA5 and MERRA-2 (Gelaro et al., 2017), which show a positive Antarctic precipitation trend from the late 20th-century into the present.

We note strong spatial similarities between our 1957-2000 reconstruction (Figure 2g) and the 1957-2000 reconstruction of MT19, where the SAM-congruent P - E trend is the dominant principal component (see Figure 1d of Medley & 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 Southern Annular Mode (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. Indeed, increasing accumulation only mitigated 59% of the sea level rise caused by dynamic ice loss from 1979-1999 (Rignot et al., 2019). From 1979-1989, 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 1989-1999, 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}. Indeed, 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 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), and many records do not span the full reconstruction period (Figure S2). Furthermore, low accumulation rates across much of EAIS preclude accurate identification of annual layers, leading to lower quality records. Indeed, 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 (Hersbach et al., 2020). 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 an insignificant EAIS mass gain trend of 5 ± 46 Gt yr^{-1} from 1992-2017; 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 that of MT19, both 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. 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), likely due to a dearth of existing ice cores (Figure 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 nonetheless 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. Extended 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 histories are also needed, such that the sensitivity of accumulation to temperature change can be accurately assessed (e.g. Nicola et al., 2023). Improving the quality of accumulation and temperature 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 non-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 estimate of ~10 mm found by Medley and Thomas (2019). As both methods 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 Antarctic sea level mitigation due to increasing accumulation 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.

Acknowledgments

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Open Research

Our archived reconstructions can be found here: https://zenodo.org/records/10030668. To produce reconstructions, we use the Last Millennium Reanalysis data assimilation framework (Hakim 2016), which is open-sourced on GitHub: https://github.com/modons/LMR. Ice core proxy data is primarily compiled in PAGES 2k consortium databases (Stenni et al., 2017; Thomas et al., 2017); water isotope records are available at https://www.ncei.noaa.gov/access/paleo-search/study/22589 and accumulation records are available at https://data.bas.ac.uk/full-record.php?id=GB/NERC/BAS/PDC/00940. 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 dataset used is the GISS Surface Temperature Analysis (Hansen et al., 2010). Reanalysis data from ERA5 (Hersbach et al., 2020) is available at: https://cds.climate.copernicus.eu/cdsapp#!/dataset/reanalysis-era5-single-levels, while MERRA-2 reanalysis data (Gelaro et al., 2017) is available at https://gmao.gsfc.nasa.gov/reanalysis/MERRA-2/.

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