Reply to reviewer comments:
Distinguishing the impacts of ozone and ozone depleting substances on the recent increase in Antarctic surface mass balance

Dear Dr. Savarino,

Thank you for considering this paper for publication in The Cryosphere. We have found the reviewers' comments insightful and helpful. Please find below a point-by-point reply (in black) to all the reviewers' comments (in blue).

## Reviewer 1

Overview: This paper used specialized climate model simulations from CESM to analyze the relative contribution of ozone depleting substances, and stratospheric and tropospheric ozone (separately) on changes in Antarctic mass balance. The study clearly demonstrates and cleanly separates that the largest contributions come from stratospheric ozone in austral summer. This is accomplished through changes in the meridional moisture flux, strongly tied to barotropic instability (rather than baroclinicity) bringing more moisture to the Antarctic continent and increasing SMB. The paper is well-written, the figures are clear, and the results are fully justified by the analysis. I only offer one small potential minor revision to help place the paper in a broader context of the model reliability, which never really was addressed or referenced. It would be helpful to know that the values and changes of SMB are well within the known bounds of SMB from satellite observations (surface height estimates etc.) and other detailed models of SMB.

We thank the reviewer for the careful reading and very useful comments.

Minor revision suggestion: 1. There is never really a discussion on how well the models employed do at simulating observed Antarctic SMB from satellite measurements or in comparison to more sophisticated models of SMB. At the very least, the LENS simulations could be compared to this over a period of overlap.

Following the reviewer's comment we now discuss the ability of the CESM to capture the Antarctic SMB (lines 39-43). Previous studies have shown that the CESM captures the spatial patterns of climatological mean Antarctic SMB, and its variability, from ice-cores and reanalysis (Lenaerts et al., 2018). Furthermore, the CESM well captures the climate response in the Southern Hemisphere to ozone-depletion (England et al., 2016; Landrum et al., 2017). This provide us confidence in using the CESM to investigate SMB changes forced by different ozone related agents.

Specific technical edits: 2. Throughout: east Antarctica, west Antarctica, and Antarctic peninsula can all be capitalized since they refer to specific proper nouns / geographic regions: East Antarctica, West Antarctica, Antarctic Peninsula

We have capitalized all 'geographic regions' (lines 84-85).

3. Line 175 – change 'show' to 'shown'

Done (line 189).

4. Some of the nomenclature is a bit awkward, particularly in Fig. 8, why not just use derivatives instead of subscripts?

We would prefer to minimize the number of symbols on each figure, and to keep the current subscripts as 'derivatives'.

## Reviewer 2

The submission has the potential to make a significant contribution to the literature, but it is not quite there yet. Before I would be able to recommend acceptance, there are a number of issues which need to be addressed.

We thank the reviewer for the careful reading and very useful comments.

Lines 12-35: Some of this literature is quite dated. In these various aspects here also make reference to the following more recent investigations – Golledge N. R. (2020) Long-term projections of sea-level rise from ice sheets. Wiley Interdisciplinary Reviews-Climate Change 11, e634, doi: 10.1002/wcc.634. Eric Rignot, Jeremie Mouginot, Bernd Scheuchl, Michiel van den Broeke, Melchior J. van Wessem and Mathieu Morlighem, 2019: Four decades of Antarctic Ice Sheet mass balance from 1979-2017. Proceedings of the National Academy of Sciences of the United States of America, 116, 1095-1103, doi: 10.1073/pnas.1812883116. Cecile Agosta, Charles Amory, Christoph Kittel, Anais Orsi, Vincent Favier, Hubert Gallee, Michiel R. van den Broeke, Jan T. M. Lenaerts, Jan Melchior van Wessem, Willem Jan van de Berg and Xavier Fettweis, 2019: Estimation of the Antarctic surface mass balance using the regional climate model MAR (1979-2015) and identification of dominant processes. Cryosphere, 13, 281-296, doi: 10.5194/tc-13-281-2019.

We thank the reviewer for bringing these papers to our attention (Agosta et al., 2019; Rignot et al., 2019; Golledge, 2020), which are now cited in the above lines (lines 14-19). Please note that Agosta et al. (2019) discussed the climatology of Antarctic SMB and focuses on year 2015, while here (including in the introduction) we discuss the trends in SMB.

Lines 24-31: Ozone depletion and associated changes in subantarctic synoptic activity have been linked with variations in the polar transport of a wide range of atmospheric constituents. To point to this broader context beneficial to cite the paper of Cataldo, M., H. Evangelista, et al., 2013: Mineral dust variability in central West Antarctica associated with ozone depletion. Atmos. Chem. Phys., 13, 2165-2175.

We thank the reviewer for this comment, and added the above reference (Cataldo et al., 2013) to the text (line 25). Indeed the effects of Ozone depletion on the atmospheric flow have not only increased the Antarctic SMB, but also the incursion of atmospheric dust into the Antarctica continent.

Lines 41-42: The paper should be clearer in describing the initial conditions (and specifically that temperature) for the different ensemble members, or this aspect should be deleted. The comments presented here are not particularly clear. Having said that, the relevant text from Jennifer Kay's 2015 CESM paper (cited here) is also somewhat unclear in saying '... spread in ensemble members 3–30 was generated by round-off level differences in their initial air temperature fields. Specifically, we applied random round-off level (order of 10**–14 K) differences to the air temperature field of ensemble member 1 to generate atmospheric initial conditions for ensemble members 3–30' (page 1337). More detail is required. E.g., was the perturbation applied independently to each grid point? Were the affected points spread over the global 3D model space, or restricted to certain models levels and/or geographical regions.

Following the reviewer's comment we further explain the construction of the CESM large ensembles (lines 47-48). For the construction of the large-ensemble described in Kay et al. (2015) the first simulation (member) is initialized from a random year in the long preindustrial control run (under 1850 forcing), and runs from 1850 to 1920 under the Historical forcing. At 1920 the other members of the ensemble branch off the first member, and are initialized with a minor change in air temperature ($\mathscr{O}10^{-14}$K). This perturbation is presented in all levels and locations (all grid points).

Lines 51-55: The analysis and results presented here are contingent on this linear assumption. This warrants some more words as to what the pitfalls and biases (e.g., introduced by self-dampening or self-amplifying processes) might be. Would be helpful here to reference some of the relevant comments in the LARMIP V2 paper of Anders Levermann, Ricarda Winkelmann, Torsten Albrecht, . . . and Roderik S. W. van de Wal 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, 35-76, doi: 10.5194/esd-11-35-2020.

Following the reviewer's comment we discuss what biases may arise from the assumption that the forcings are linearly additive (lines 61-63). As discussed in Levermann et al. (2020), by assuming additivity we neglect any self-dampening or self-amplifying processes of each forcing agent: our approach assumes that the SMB responses to different forcings are additive, and thus that the effects of non-linear interactions between forcings can be ignored. However, as discussed in Levermann et al. (2020), since we are investigating the SMB forced response to external forcings, rather its internal variability, we reduce these internal processes and increase the linearity of the results. Furthermore, the comparison between each individual forcing experiment and the 'All' experiment, allow us to assess whether such self-amplifying/decaying processes are not represented in the overall response.

Lines 62-63: Delete parenthetical comment. Acronym SMB has essential already been defined (at line

15).

Done.

Line 72 (Figure 2): Valuable and informative plots here for annual case. Might be useful to plot the ‘zero line’ on these. The plots show a great deal of white, but one is not sure what parts are showing increases versus decreases. Regarding the statistical significance of the changes, the panels for the three forcing experiments (b – d) show, e.g., significant changes centered on the 180E meridian from the RIS to the pole, while no such significance is displayed in the ‘All’ case. This may be OK (I haven’t thought this thru) but at first sight looks strange, and is worth checking. It may be that the values are negative in the ‘O3 strat’ case (while they are unambiguously positive I panels b and d. Showing the zero line would help with this possible riddle.

Following the reviewer’s comment we have further amplified the colors in Fig. 2 and added the zero lines. The great deal of white in these plots are a result of the large SMB changes in the Antarctic periphery, with minor changes inland. Note that ’All’ includes not only the forcing agents that we explore here (ODS and ozone), but all other anthropogenic or natural forcing agents (e.g., greenhouse gases). Thus, not necessarily changes in ODS and ozone could explain the changes when accounting for all forcing agents.

Line 93: Replace ‘mb’ with ‘hPa’. (Similar comment throughout the Ms, including lines 84, 96, 102, 139, 156, . . .)

Done.

Lines 105-110: In equn (1) use extra nested parentheses to make clear that the vertical integral is taken over all terms in the integrand and not just the last one. Also, the RHS of the equation gives the (mathematical) convergence of moisture at latitude phi. This latitude dependence must be indicated on the LHS, as well as what infinitesimal area is being considered here. (The flux convergence relationship with P-E only make sense when a finite area is being considered.) Appropriate overbars are required on symbols in the legends in Figure 5, as well as in the caption.

Following the reviewer’s comment we added extra parentheses to Eq. 1, and the LHS dependence in latitude. The convergence is over the meridional grid cell length (lines 120-121), and we added overbars to Figs. 4 and 5.

Lines 112-124: Some of this material is poorly expressed and misleading. The net flux of moisture into the polar ‘cap’ (poleward of 65S), can actually be determined directly from the flux across 65S. The authors comment that changes in this net flux can be used to account for changes in SMB mostly over the Antarctic continent. This statement is very misleading. The seas around Antarctic are host to intense and frequent storms (make reference here to compilation of Keay et al., 2003: Synoptic activity in the seas around Antarctica. Mon. Wea. Rev., 131, 272-288). These are associated with large P-E in those subantarctic waters (and certainly south of 65S). Hence, a priori, the net precip south of that latitude cannot be regarded as a proxy for SMB over the content itself. In justifying this association, the authors cite the correlation of these two P-Es, but do not compare their MAGNITUDES. A quick calculation reveals these to be very different. The 65S polar cap covers about 25 million km**2. A flux of 0.1 mm/day (a typical value in Figure 4) gives a volume of water of 10**-4 m/day * 25 x 10**12 m**2 = 2.5 x 10**9 m**3/day. This is 2.5 Gt/day or 910 Gt/yr. This is about 3 times larger than the 300 Gt/yr (for 0.1 mm/day) indicated in Figure 4. This means that about two thirds of the vapor which crosses 65S precipitates into the ocean before it reaches the continent. While one MIGHT expect that if the total flux 65S changes by a certain fraction the PE over the continent would change by a similar fraction. However this important part of the text must be expressed and justified more clearly. I appreciate that calculating eddy fluxes across latitudes in much easier than across irregular boundaries (like the Antarctic coast), and I have no great problem with what the authors have done. My main point is that they should be much more upfront with the caveats, and be clear on the synoptics in this complex part of the world.

Following the reviewer’s comment we further explain the biases resulted from using zonal mean approach on a non-zonal problem (lines 121-130). When computing the moisture budget analysis we define eddies as deviation from zonal mean. Thus, the P-E problem only hold under zonal averaging. As the reviewer mentioned, the Antarctic coast line is not zonally symmetric, and thus our analysis indeed cover areas of water, and not only land as in the SMB calculation. The choice of 65S as the lower boundary for the analysis is twofold. On the one hand, the southern boundary should account for the Antarctic periphery where most of the SMB changes occur (Fig. 2 in the manuscript). On the other hand, the southern boundary should not be too far away towards the equator, in order to exclude open water areas as much as possible. Indeed, the magnitude of zonal mean P-E and SMB will not be identical (due to P-E processes over ocean; subantarctic regions accounts for a large portion of the Southern Ocean storms, Simmonds et al., 2003), however, the linear and high correlation between the two indicates that the processes over the ocean are linearly related to the process over land. Thus, changes in P-E could, to the very least, point us to which physical processes are mostly important in modifying the SMB.

Lines 118-124: Reinforce this message by refencing the study of Grieger, Leckebusch, et al., 2018: Subantarctic cyclones identified by 14 tracking methods, and their role for moisture transports into the continent. Tellus, 70A, 1454808, doi: 10.1080/16000870.2018.1454808 which demonstrates strong positive summer trends in subantarctic cyclone numbers (in association in increasing SAM), and their role in poleward moisture transport. Also valuable here to cite here the analysis of Papritz, Wernli et al. 2014: The role of extratropical cyclones and fronts for Southern Ocean freshwater fluxes. J. Clim., 27, 6205-6224 exploring the SH relationships between synoptic eddies and P-E.

Following the reviewer's comment we now cite the above studies (lines 138-140), which show the important and increasing role of eddies in converging more moisture water into the Antarctic (Papritz et al., 2014; Grieger et al., 2018).

Lines 153-166: Some interesting conclusions are reached here in connection with the relative importance of baroclinic and barotropic instability in driving the moisturetransporting transient eddies. I have a few issues with how this comparison was made. For the baroclinic part the authors calculate the delta vertical wind shear as the zonal wind difference between upper (300mb-500mb) and lower (600mb-800mb) levels. This will be very similar to the difference between 400 and 700 hPa, or an estimate of the baroclinicity at 550 hPa. The total moisture transport is dominated by the lower levels of the troposphere, and the 850 hPa level (which is frequently chosen for applications such as this) would be a much more appropriate level to take. For the barotropic instability case, the text states the this is determined from the 'vertically averaged delta uyy'. It is not clear whether this average was taken through the entire atmosphere and/or why were not some key atmospheric levels chosen for this. At the very least the authors should determine their baroclinicity at a more physically-consistent level, and justify why a similar level should not be used for the barotropic component. As it stands, the analysis has not convinced me that it '. . . suggests that increased barotropic instability is the primary mechanism via which ozone depletion enhances the eddy-moisture flux, resulting in a larger Antarctic SMB over the second half of the 20th century

Following the reviewer's comment we added the 850hPa level to the calculation of the vertical wind shear, and state that the barotropic component is vertically integrated through the entire atmosphere (lines 169 and 171). We would prefer to keep the baroclinic upper and lower levels, rather choosing specific levels for the vertical gradient. The reason is that we would not want our analysis to be level dependent. For the barotropic component, note that one should not choose specific levels as by definition the barotropic component is the vertically integrated (through the entire troposphere) part of the flow (i.e., it is depth independent), as mentioned in the text. Note that not only eddy moisture fluxes show high correlation with changes in uyy, but ensembles accounting for ozone depletion show a significant increases in uyy relative to ensembles that lack ozone depletion. Such distinct behaviors are not presented in the metric for baroclinic instability.

Lines 179: After '. . . gradient of the mean relative vorticity' insert 'of the zonal flow'. (This connection has only been shown for uyy.)

By construction the zonal mean relative vorticity accounts only for the zonal flow (line 193).

We would like to emphasize again our gratitude to the reviewers who pointed us in important directions that have significantly improved this manuscript.

Sincerely,

Rei Chemke, Michael Previdi, Mark England and Lorenzo Polvani

# References

Agosta, C., Amory, C., Kittel, C., Orsi, A., Favier, V., Gallée, H., van den Broeke, M. R., Lenaerts, J. T. M., Melchior van Wessem, J., van de Berg, W. J., and Fettweis, X. (2019). Estimation of the Antarctic surface mass balance using the regional climate model MAR (1979-2015) and identification of dominant processes. *The Cryosphere*, 13(1):281–296.

Cataldo, M., Evangelista, H., Simões, J. C., Godoi, R. H. M., Simmonds, I., Hollanda, M. H., Wainer, I., Aquino, F., and Van Grieken, R. (2013). Mineral dust variability in central West Antarctica associated with ozone depletion. *Atmos. Chem. Phys.*, 13(4):2165–2175.

England, M. R., Polvani, L. M., Smith, K. L., Landrum, L., and Holland, M. M. (2016). Robust response of the Amundsen Sea Low to stratospheric ozone depletion. *Geophys. Res. Lett.*, 43(15):8207–8213.

Golledge, N. R. (2020). Long-term projections of sea-level rise from ice sheets. *Wiley Interdiscip. Rev.: Climate Change*, 11(2):e634.

Grieger, J., Leckebusch, G. C., Raible, C. C., Rudeva, I., and Simmonds, I. (2018). Subantarctic cyclones identified by 14 tracking methods, and their role for moisture transports into the continent. *Tellus*, 70(1):1454808.

Kay, J. E., Deser, C., Phillips, A., Mai, A., Hannay, C., Strand, G., Arblaster, J. M., Bates, S. C., Danabasoglu, G., Edwards, J., Holland, M., Kushner, P., Lamarque, J.-F., Lawrence, D., Lindsay, K., Middleton, A., Munoz, E., Neale, R., Oleson, K., Polvani, L., and Vertenstein, M. (2015). The Community Earth System Model (CESM) Large Ensemble Project: A Community Resource for Studying Climate Change in the Presence of Internal Climate Variability. *Bull. Am. Meteor. Soc.*, 96:1333–1349.

Landrum, L. L., Holland, M. M., Raphael, M. N., and Polvani, L. M. (2017). Stratospheric Ozone Depletion: An Unlikely Driver of the Regional Trends in Antarctic Sea Ice in Austral Fall in the Late Twentieth Century. *Geophys. Res. Lett.*, 44(21):11,062–11,070.

Lenaerts, J. T. M., Fyke, J., and Medley, B. (2018). The Signature of Ozone Depletion in Recent Antarctic Precipitation Change: A Study With the Community Earth System Model. *Geophys. Res. Lett.*, 45(23):12,931–12,939.

Levermann, A., Winkelmann, R., Albrecht, T., Goelzer, H., Golledge, N. R., Greve, R., Huybrechts, P., Jordan, J., Leguy, G., Martin, D., Morlighem, M., Pattyn, F., Pollard, D., Quiquet, A., Rodehacke, C., Seroussi, H., Sutter, J., Zhang, T., Van Breedam, J., Calov, R., DeConto, R., Dumas, C., Garbe, J., Hilmar Gudmundsson, G., Hoffman, M. J., Humbert, A., Kleiner, T., Lipscomb, W. H., Meinshausen, M., Ng, E., Nowicki, S. M. J., Perego, M., Price, S. F., Saito, F., Schlegel, N., Sun, S., and van de Wal, R. S. W. (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.

Papritz, L., Pfahl, S., Rudeva, I., Simmonds, I., Sodemann, H., and Wernli, H. (2014). The Role of Extratropical Cyclones and Fronts for Southern Ocean Freshwater Fluxes. *J. Climate*, 27(16):6205–6224.

Rignot, E., Mouginot, J., Scheuchl, B., van den Broeke, M., van Wessem, M. J., and Morlighem, M. (2019). Four decades of Antarctic Ice Sheet mass balance from 1979-2017. *Proc. Natl. Acad. Sci. U.S.A.*, 116(4):1095–1103.

Simmonds, I., Keay, K., and Lim, E. (2003). Synoptic Activity in the Seas around Antarctica. *Mon. Weath. Rev.*, 131(2):272.

# Distinguishing the impacts of ozone and ozone depleting substances on the recent increase in Antarctic surface mass balance

Rei Chemke[1], Michael Previdi[2], Mark R. England[3,4], and Lorenzo M. Polvani[1,2]

[1]Department of Earth and Planetary Sciences, Weizmann Institute of Science, Rehovot, Israel
[2]Lamont-Doherty Earth Observatory, Columbia University, Palisades, NY 10964, USA
[3]Department of Climate, Atmospheric Science, and Physical Oceanography, Scripps Institution of Oceanography, UCSD, La Jolla, CA, USA
[4]Department of Physics and Physical Oceanography, University of North Carolina Wilmington, NC, USA

**Correspondence:** R. Chemke (rc3101@columbia.edu)

**Abstract.** The Antarctic surface mass balance (SMB) has global climatic impacts through its effects on global sea-level rise. The forced increase in Antarctic SMB over the second half of the 20th century was argued to stem from multiple forcing agents, including ozone and ozone-depleting substances. Here we use ensembles of fixed-forcing model simulations to quantify and contrast the contributions of stratospheric ozone, tropospheric ozone and ozone-depleting substances (ODS) to increases in the Antarctic SMB. We show that ODS and stratospheric ozone make comparable contributions, and together account for 44% of the increase in the annual mean Antarctic SMB over the second half of the 20th century. In contrast, tropospheric ozone has an insignificant impact on the SMB increase. A large portion of the annual mean SMB increase occurs during Austral summer, when stratospheric ozone is found to account for 63% of the increase. Furthermore, we demonstrate that stratospheric ozone increases the SMB by enhancing the meridional mean and eddy flows towards the continent, thus converging more water vapor over the Antarctic.

## 1 Introduction

Being the largest freshwater reservoir on Earth, the Antarctic ice sheet is potentially the largest contributor to future global sea level rise (IPCC, 2013; Fretwell et al., 2013). By 2100, the projected loss of Antarctic land-ice due to dynamical processes (i.e., the flow of the ice sheet) will increase sea level by up to 185 mm (IPCC, 2013; Golledge, 2020). In contrast, the projected increase in Antarctic surface mass balance (SMB, i.e., the larger increase in precipitation vs. evaporation/sublimation; e.g., see Agosta et al., 2019) will reduce this sea level rise by 20-80-mm (Krinner et al., 2007; Uotila et al., 2007; Ligtenberg et al., 2013; Frieler et al., 2015; Previdi and Polvani, 2016; Palerme et al., 2017). Over recent decades, however, only the dynamical mass loss due to the acceleration of outlet glaciers has been documented (Rignot et al., 2004; Shepherd et al., 2012; Velicogna et al., 2014; Wouters et al., 2015; Rignot et al., 2019); the Antarctic SMB has exhibited insignificant trends (Monaghan et al., 2006a, b; Lenaerts et al., 2012), and thus has yet to mitigate sea-level rise. Although climate models do simulate an increase in Antarctic SMB over recent decades in response to the external forcings (Krinner et al., 2007; Monaghan et al., 2008; Palerme et al., 2017; Previdi and Polvani, 2017), such an increase has been obscured by the large climate variability (Previdi and Polvani, 2016), resulting in insignificant observed Antarctic SMB trends (Frezzotti et al., 2013).

Similar to most late 20th century forced changes in the Southern Hemisphere (Polvani et al., 2011b), the modeled increase in Antarctic SMB**, and incursion of dust particles into the Antarctic continent (Cataldo et al., 2013),** has also been attributed to anthropogenic emissions. In particular, two recent studies have argued for the importance of increases in the emissions of ozone-depleting substances (ODS) (Previdi and Polvani, 2017) and in stratospheric ozone depletion (Lenaerts et al., 2018) for Antarctic SMB. However, neither study cleanly isolated the effects of these forcing agents: Previdi and Polvani (2017) did not separate the effects of ODS from stratospheric ozone, while Lenaerts et al. (2018) did not separate the effects of stratospheric from tropospheric ozone. This, together with the fact that different seasons were analyzed in these two studies, has prevented a clear attribution of the forced SMB increase. In addition, a quantitative analysis of the mechanism underlying the forced increase in SMB has not been conducted to date.

The aim of this paper is thus to elucidate which forcing agents related to ozone have mostly contributed to the forced increase in Antarctic SMB over the second half of the 20th century, and to quantitatively analyze the underlying mechanisms. This is done using ensembles of fixed-forcing simulations which allow us to disentangle the impacts of stratospheric ozone depletion, tropospheric ozone changes, and ODS emissions on Antarctic SMB trends.

## 2 Methods

We analyze four ensembles of model simulations using the Community Earth System Model (CESM1) (Hurrell et al., 2013): each ensemble is forced with slightly different agents. **We use this CMIP5-class model as previous work showed that the CESM captures the spatial patterns of climatological mean Antarctic SMB, and its variability, from ice-cores and reanalysis (Lenaerts et al., 2018). Furthermore, the CESM well captures the climate response in the Southern Hemisphere to ozone-depletion (England et al., 2016; Landrum et al., 2017). This provide us confidence in using the CESM to investigate SMB changes under forced ozone changes.**

The first ensemble consists of 10 members, which were randomly picked from the 40-member large-ensemble (LENS) described in Kay et al. (2015). Each member is forced, from 1920 to 2005, with all known natural and anthropogenic forcings, following the Historical specifications of the Climate Modeling Intercomparison Project, Phase 5 (Taylor et al., 2012). While all simulations are subjected to the same forcing, they differ in their initialization: **each member is initialized at 1920 with a slightly different air temperature** ($\mathcal{O}10^{-14}\,\mathrm{K}$**, across all grid points),** thus allowing us to investigate the climate's transient response to the external forcing in the presence of internal climate variability.

The other three ensembles are identical to the LENS, but without time evolution of specific forcing agents: a 10-member ensemble with fixed ODS (Fix-ODS, Polvani et al., 2020), a 10-member ensemble with fixed ODS and stratospheric ozone ($\mathrm{Fix\text{-}ODS\&O3_{strat}}$, Polvani et al., 2020), and an 8-member ensemble with fixed stratospheric and tropospheric ozone (Fix-O3, England et al., 2016; Landrum et al., 2017; Lenaerts et al., 2018). These forcing agents are fixed at 1955 values (pre-ozone hole). Each simulation in the fixed forcing ensembles is initialized from the corresponding simulation of the LENS at 1950.

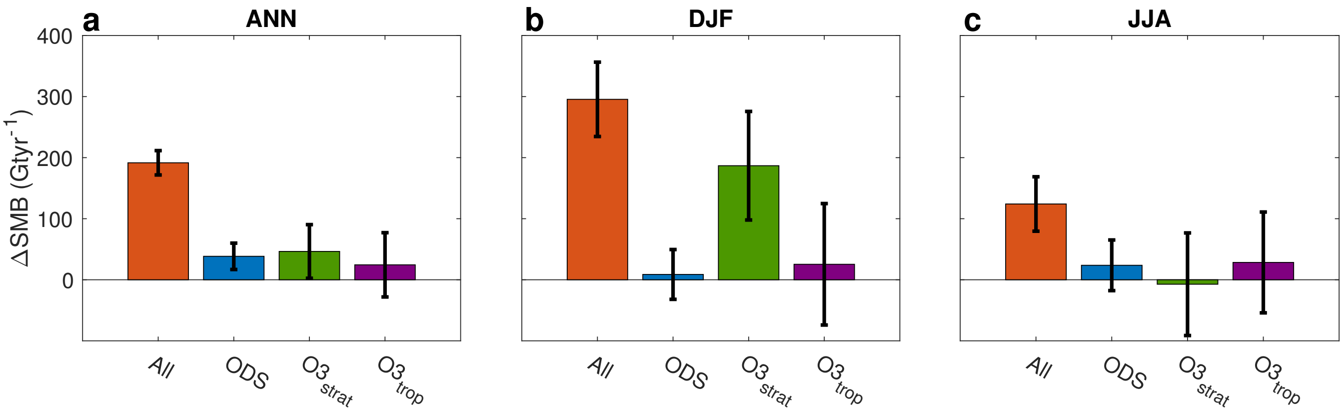

**Figure 1.** Antarctic SMB response to second half of the 20th century forcing ($\Delta\mathrm{SMB}$) in (a) annual mean, (b) DJF and (c) JJA. Red bars show the response in the full forcing ensemble mean (All). The blue, green and purple bars show the contributions of ODS, stratospheric ozone ($\mathrm{O3_{strat}}$), and tropospheric ozone ($\mathrm{O3_{trop}}$) to the SMB response, respectively. Error bars represent the 95% confidence interval.

Thus, the ensemble mean difference between LENS and Fix-ODS, averaged over 1990-2005, allows one to isolate and quantify the effects of ODS over the second half of the 20th century. Similarly, the ensemble mean difference between Fix-ODS and $\mathrm{Fix\text{-}ODS\&O3_{strat}}$ isolates the effects of stratospheric ozone ($\mathrm{O3_{strat}}$). Finally, subtracting the effects of stratospheric ozone from the ensemble mean difference between LENS and Fix-O3 isolates the effects of tropospheric ozone ($\mathrm{O3_{trop}}$). This procedure assumes that the forcings are linearly additive and, it should be clear, the model runs analyzed here were not originally designed for this study; rather, we are here simply exploiting these "ensembles of opportunity" which were designed for earlier studies (Polvani et al., 2020; England et al., 2016) to study the effect of three distinct forcing agents on the Antarctic SMB. **It should be noted that our approach assumes that the SMB responses to different forcings are additive, and thus that the effects of non-linear interactions between forcings can be ignored (Levermann et al., 2020).**

Throughout the manuscript, $\Delta$ represents the response of the climate system to the forcings, which is defined as the difference between the 1990-2005 period in each ensemble member and the 1940-1955 period in the corresponding member of the LENS. Thus, the response in LENS accounts for the effects of all Historical forcing agents (hereafter referred to as All). We choose the 1990-2005 and 1940-1955 periods in order to examine the SMB response to historical forcing during the second half of the 20th century, when the entire response to ODS/ozone forcing occurs.

## 3 The role of ozone vs. ODS in increasing the annual mean Antarctic SMB

We start by quantifying the contribution of each forcing agent to the Antarctic annual mean $\Delta\mathrm{SMB}$ (Fig. 1a). Recall that while stratospheric ozone impacts the troposphere, primarily, by shifting the eddy-driven jet towards the South pole in summer, the impact of ODS and tropospheric ozone is primarily a warming of the surface temperatures. We focus first on the annual mean response, as it is the most relevant for changes in sea-level rise. In the All ensemble the annual mean $\mathrm{SMB}$ increases by 191.6

$\mathrm{Gtyr}^{-1}$ over the second half of the 20th century (red bar), and ODS and stratospheric ozone make comparable contributions to the annual mean Antarctic SMB increase. Validating the results of Previdi and Polvani (2017) with a different model, we find that the increased emissions of ODS account for $20\%$ (38.4 $\mathrm{Gtyr}^{-1}$) of the annual mean SMB increase (blue bar); stratospheric ozone depletion accounts for $24.2\%$ (46.4 $\mathrm{Gtyr}^{-1}$) of the annual mean SMB increase (green bar). Tropospheric ozone, on the other hand, shows a statistically insignificant contribution of only $12.7\%$ (24.5 $\mathrm{Gtyr}^{-1}$); increases in tropospheric ozone are associated with air pollution, and thus are mostly concentrated in the Northern Hemisphere. Thus, ODS and stratospheric ozone together account for $\sim 44\%$ of the annual mean Antarctic SMB increase over the period of interest; the other $\sim 56\%$ of the increase is caused by other forcings dominated by increases in $\mathrm{CO}_2$.

To further investigate the effects of ODS and ozone depletion on the annual mean SMB, we next examine the spatial pattern of $\Delta\mathrm{SMB}$ (Fig. 2). In the All ensemble the SMB increase mostly occurs in the Antarctic coastline, and over nearly all longitudes (green colors in Fig. 2a). While ODS (Fig. 2b) and tropospheric ozone (Fig. 2d) mostly increase the SMB over **West Antarctica**, stratospheric ozone increases it over **East Antarctica** and the **Antarctic Peninsula** (Fig. 2c). Thus, while ODS and stratospheric ozone have comparable impacts on the annual mean area integrated $\Delta\mathrm{SMB}$ (Fig. 1), it is the stratospheric ozone that is mostly responsible for the circumpolar increase of the SMB over the second half of the 20th century (Lenaerts et al., 2018).

Being powerful greenhouse gases, ODS increase the SMB by warming and moistening the Antarctic atmosphere, thus allowing for more snowfall (Previdi and Polvani, 2017). However, the reason for the SMB increase due to stratospheric ozone is less clear, and thus we next elucidate the underlying mechanism. Given the strong seasonal signal of ozone depletion, one would expect that its effects on the SMB would peak during Austral summer (December-February, DJF); the ozone hole itself initially develops during spring, but its tropospheric impacts are delayed until summer (Previdi and Polvani, 2014). Fig. 1b and c show $\Delta\mathrm{SMB}$ during DJF and June-August (JJA). Indeed in the All ensemble (red bars) the largest increase in SMB of 295.5 $\mathrm{Gtyr}^{-1}$ occurs in DJF, compared with an increase of 124.1 $\mathrm{Gtyr}^{-1}$ in JJA. Unlike the annual mean case, in DJF stratospheric ozone alone accounts for the majority ($63.2\%$) of the total SMB increase, and is more important than $\mathrm{CO}_2$. In comparison, ODS (blue bar) and tropospheric ozone (purple bar) have only minor effects on the DJF $\Delta\mathrm{SMB}$.

## 4 Elucidating the effects of stratospheric ozone on Antarctic SMB

In this section we explore the mechanism by which ozone depletion increases the Antarctic SMB, focusing our analysis on the DJF season when the ozone signal is strongest. Recently, Lenaerts et al. (2018) suggested that ozone depletion acts to increase, across most longitudes, the meridional geopotential height gradient at 500 hPa (associated with the zonal geostrophic wind), which they claimed was responsible for the circumpolar increase in DJF Antarctic SMB. This conclusion was based on the ensemble mean difference between the same full forcing (All) and Fix-O3 ensembles that are considered in the current study. To examine the robustness of that conclusion we follow Lenaerts et al. (2018), and show in Fig. 3 the difference in 500 hPa geopotential height (contours) and SMB (colors) between the All and the Fix-O3 experiments over the period 1986-2005 for each of the eight different ensemble members, and for the ensemble mean.

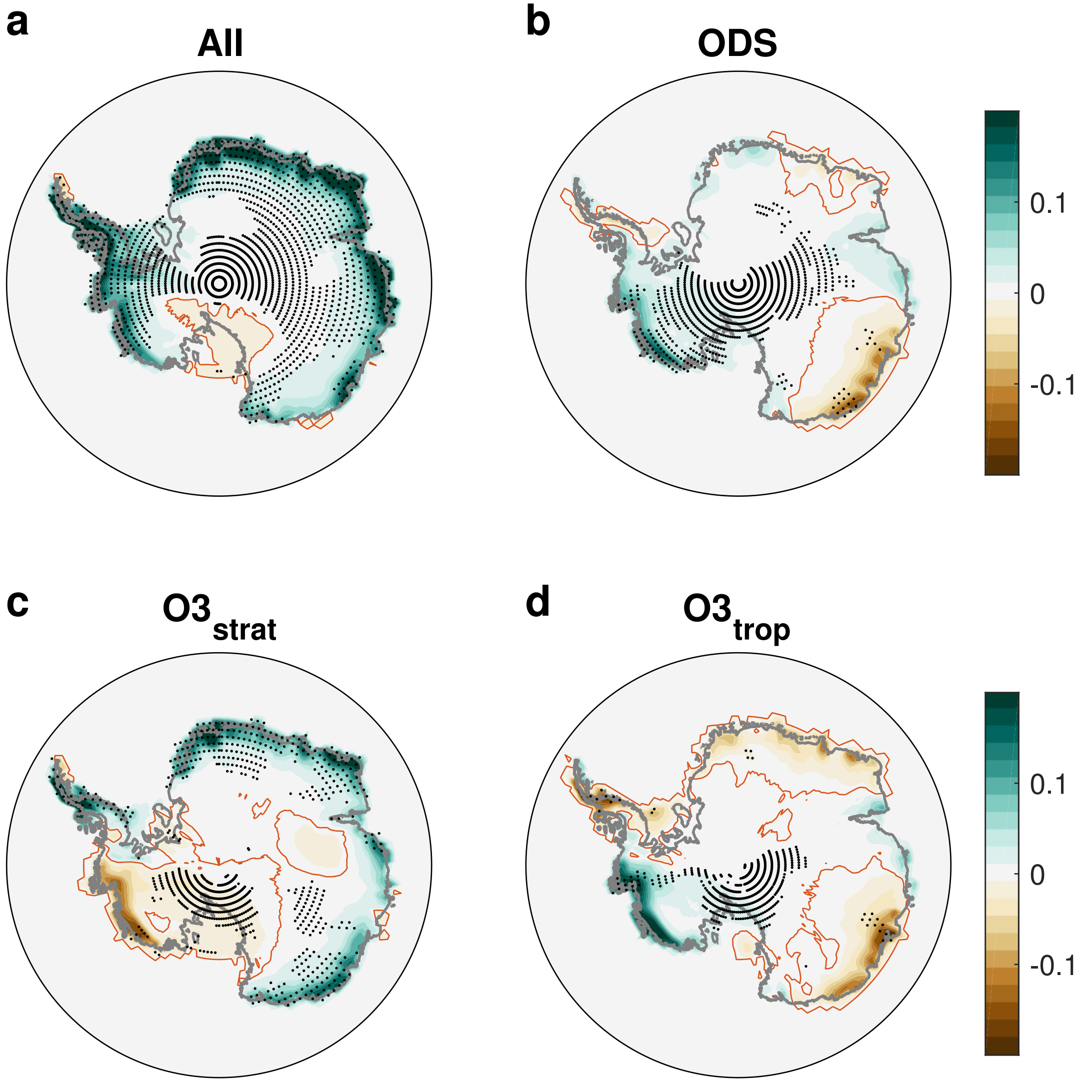

**Figure 2.** (a) Annual mean Antarctic SMB response to second half of the 20th century forcing ($\Delta\mathrm{SMB}$, $\mathrm{Gtyr}^{-1}$) in the full forcing ensemble mean (All). Panels (b)-(d) show the contributions of ODS, stratospheric ozone ($\mathrm{O3}_{\mathrm{strat}}$), and tropospheric ozone ($\mathrm{O3}_{\mathrm{trop}}$) to the SMB response, respectively. **Solid red lines mark the zero line.** The small black dots show where the response is statistically significant at the 95% confidence level.

As in Lenaerts et al. (2018) (cf. their Fig. 2), the ensemble mean indeed shows an increase in the meridional geopotential height gradient and SMB across most longitudes. However, while all members show an increase in SMB around the Antarctic continent, only half of the members (#3,4,6 and 7) show a circumpolar increase in the meridional geopotential height gradient. This suggests that changes in the spatial patterns of the zonal geostrophic wind at 500 hPa are not robust across ensemble

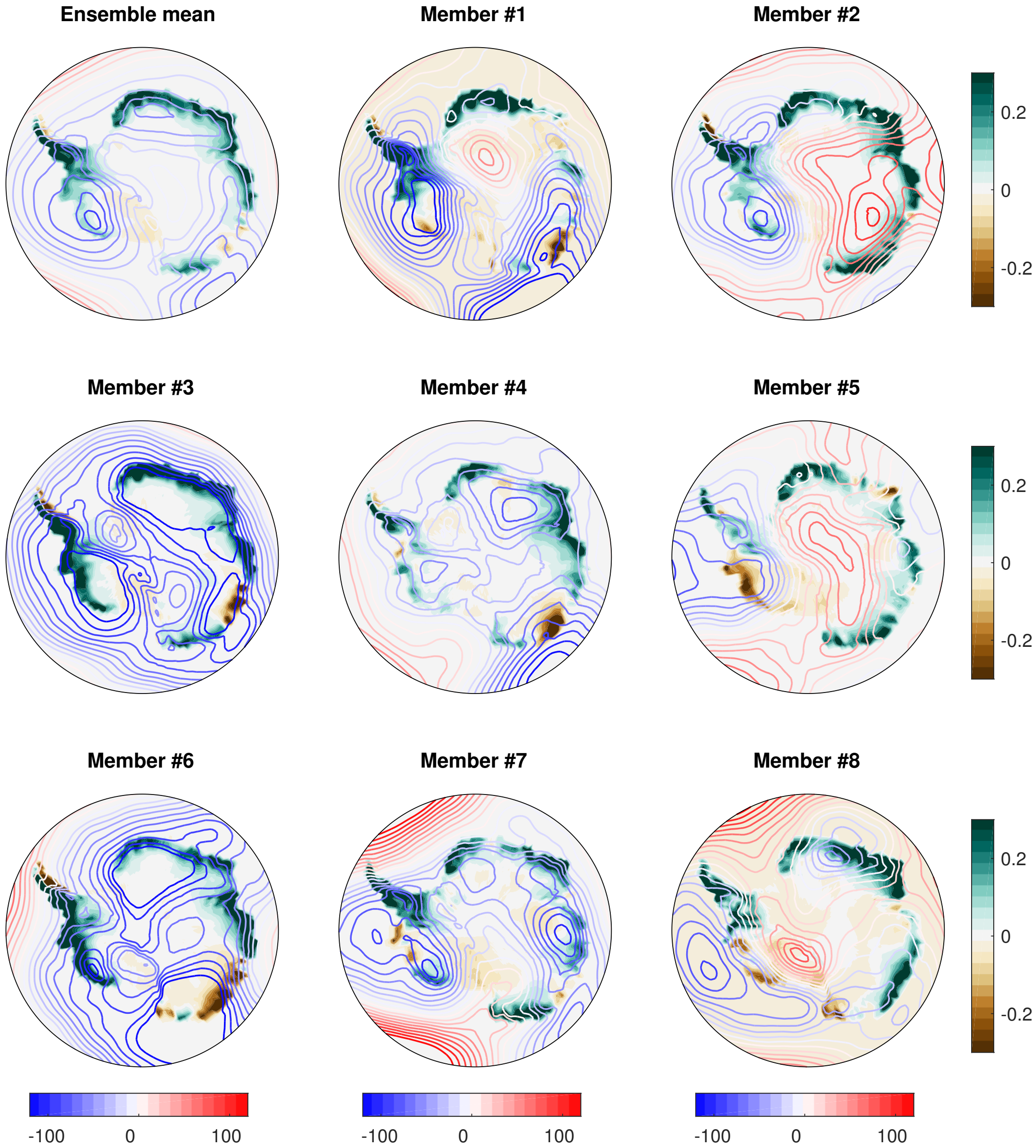

**Figure 3.** The difference in DJF Antarctic SMB (shading, $\mathrm{Gtyr}^{-1}$) and 500 hPa geopotential height (contours, $\mathrm{m}^2\mathrm{s}^{-2}$) between the full forcing ensemble (All) and the fixed stratospheric and tropospheric ozone ensemble (Fix-O3), averaged over the period 1986-2005.

members. In any case, it is changes in the meridional convergence of moisture flux - and not changes in the mean zonal flow - that directly affect the zonal mean SMB (as shown below). We examine these meridional moisture flux changes next.

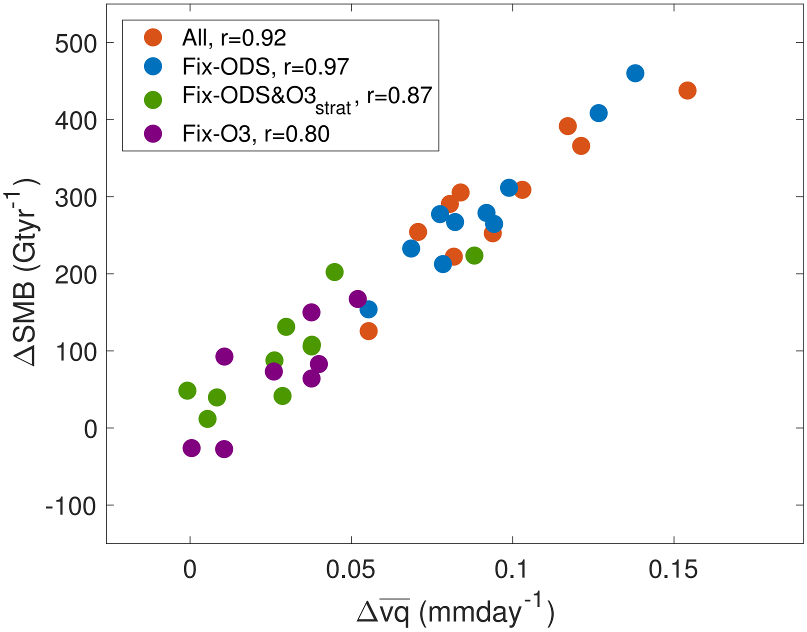

**Figure 4.** The response over the second half of the 20th century forcing of the DJF SMB ($\Delta\mathrm{SMB}$) as a function of the meridional moisture flux convergence ($\Delta\overline{vq}$) in the full forcing ensemble (All, red), fixed ODS ensemble (Fix-ODS, blue), fixed ODS and stratospheric ozone ensemble (Fix–ODS&O3$_{\mathrm{strat}}$, green) and fixed stratospheric and tropospheric ozone ensemble (Fix-O3, purple). Correlations appear at the upper left corner.

Changes in the surface precipitation-minus-evaporation (P-E; equivalent to the SMB over Antarctica) can be analyzed using the zonal mean vertically integrated moisture equation (e.g., Trenberth and Guillemot, 1995; Seager et al., 2010),

$$\Delta\left(\overline{P}(\phi)-\overline{E}(\phi)\right) = -\frac{1}{ga\cos\phi}\frac{\partial}{\partial\phi}\Big\{\int_{o}^{p_s}\left([\overline{v}]\,\Delta\overline{q}+[\overline{q}]\,\Delta\overline{v}+\Delta\overline{v'q'}\right)\cos\phi dp\Big\}, \qquad (1)$$

where over bar represents zonal and DJF means, $g$ is gravity, $a$ is Earth's radius, $\phi$ is latitude, $p_s$ is surface pressure, $v$ is the meridional velocity, $q$ is specific humidity, square brackets represent time mean calculated across the combined 1990-2005 and 1940-1955 periods, and prime represents deviation from zonal and monthly mean (i.e., transient and stationary eddies). The first term on the righthand side of Eq. 1 accounts for changes in the mean moisture ($\overline{v}\Delta\overline{q}$), the second for the changes in meridional velocity ($\overline{q}\Delta\overline{v}$), and the third term accounts for changes in eddy moisture flux ($\Delta\overline{v'q'}$). **The convergence of each term on the righthand side is calculated over all latitudes. Note that $\overline{P}-\overline{E}$ is not identical to SMB (zonal mean $P-E$ vs area integrated $P-E$ over only the Antarctic continent), as it accounts for processes that occurs over the ocean (subantarctic regions accounts for a large portion of the Southern Ocean storms). To minimize this difference here we average each term in Eq. 1 between $65°\mathrm{S}-90°\mathrm{S}$ to account for changes in $\overline{P}-\overline{E}$ mostly over the Antarctic continent. As a result, while changes in the total meridional moisture flux convergence ($\Delta\overline{vq}$, i.e., the sum of the right hand side terms in Eq. 1) are larger in magnitude than $\Delta\mathrm{SMB}$, they are highly correlated with $\Delta\mathrm{SMB}$ as one can see in Fig. 4 ($r=0.92$**

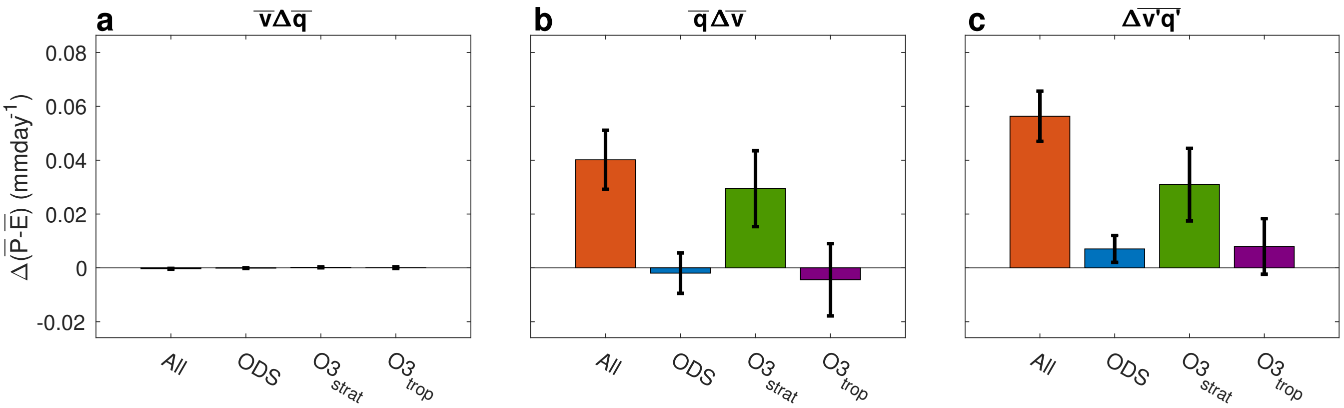

**Figure 5.** The contributions to the increase in DJF Antarctic $\overline{P}-\overline{E}$, $\Delta\left(\overline{P}-\overline{E}\right)$, arising from changes in (a) mean moisture ($\overline{v}\Delta\overline{q}$), (b) mean meridional circulation ($\overline{q}\Delta\overline{v}$) and (c) eddy moisture flux ($\Delta\overline{v'q'}$). Red bars show the response in the full forcing ensemble mean. The blue, green and purple bars show the contributions of ODS, stratospheric ozone ($\mathrm{O3_{strat}}$), and tropospheric ozone ($\mathrm{O3_{trop}}$) to the P-E response, respectively. Error bars represent the 95% confidence interval.

**in All,** $r = 0.97$ **in Fix-ODS,** $r = 0.87$ **in** $\mathrm{Fix\text{-}ODS\&O3_{strat}}$ **and** $r = 0.80$ **in Fix-O3). The strong correlation between** $\Delta\overline{vq}$ **and** $\Delta\mathrm{SMB}$ **suggests that the zonal mean moisture budget (i.e., Eq. 1) can provide meaningful insight into the physical processes driving Antarctic SMB changes (** $\overline{P}-\overline{E}$ **processes over the ocean are linearly related to** $\overline{P}-\overline{E}$ **processes over land).**

Figure 5 shows the contribution of each term in Eq. 1 to changes in DJF Antarctic $\overline{P}-\overline{E}$. First we focus on the response to all forcings (red bars). Moisture changes in DJF have only a minor effect on $\Delta\left(\overline{P}-\overline{E}\right)$ ($-0.03\cdot10^{-2}\,\mathrm{mmday}^{-1}$, red bar in Fig. 5a), in contrast to changes in the mean meridional velocity ($4\cdot10^{-2}\,\mathrm{mmday}^{-1}$, Fig. 5b) and eddy moisture flux ($5.6\cdot10^{-2}\,\mathrm{mmday}^{-1}$, Fig. 5c), which have a comparatively large effect. Second, similar to DJF $\Delta\mathrm{SMB}$ (Fig. 1b), ODS (blue bars) and tropospheric ozone (purple bars) have minor effects on $\Delta\left(\overline{P}-\overline{E}\right)$, in contrast to stratospheric ozone which has a relatively large effect (green bars). Specifically, ozone depletion is found to account for $73.3\%$ ($2.9\cdot10^{-2}\,\mathrm{mmday}^{-1}$) and $54.9\%$ ($3.1\cdot10^{-2}\,\mathrm{mmday}^{-1}$) of the mean meridional velocity and eddy moisture flux contributions to the total in DJF, respectively. **This corroborates the results of previous studies who showed the important and increasing role of eddies, driven by ozone depletion, in converging more moisture into the Antarctic (Papritz et al., 2014; Grieger et al., 2018), and thus, as shown here, increasing the SMB by enhancing snowfall.**

Finally we ask: how does ozone depletion enhance the meridional flow? Previous studies have shown that by increasing the meridional temperature gradient aloft, ozone depletion acts to enhance the mean zonal wind on the poleward flank of the jet (e.g., Polvani et al., 2011b). This enhanced zonal wind is not confined to the upper levels but reaches all the way to the surface. Fig. 6 shows the response in DJF mean zonal wind ($\Delta\overline{u}$) to the various forcings. In the historical (All) integrations, the mean zonal wind intensifies over the poleward flank of the jet (panel a), and this response is driven almost entirely by stratospheric ozone depletion (Fig. 6c).

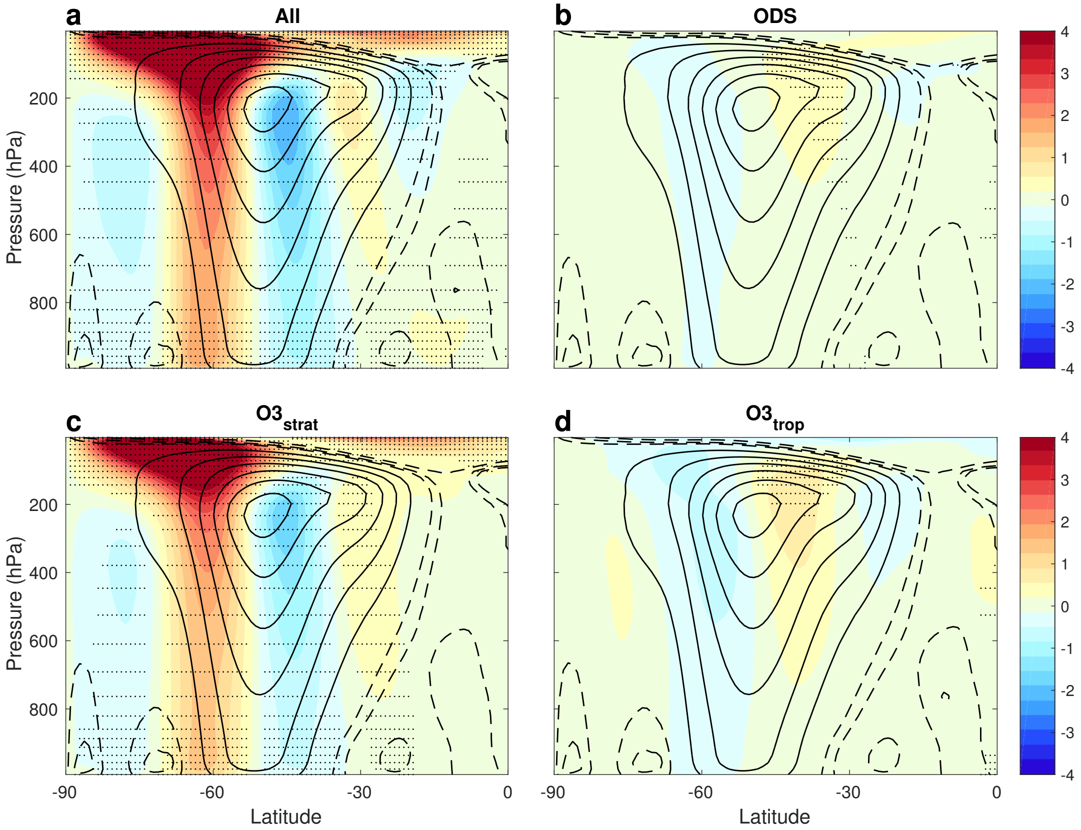

**Figure 6.** (a) The response over the second half of the 20th century forcing of the DJF zonal mean zonal wind ($\Delta\overline{u}$, $\mathrm{ms}^{-1}$) in the All forcing ensemble mean. Panels (b)-(d) show the contributions of ODS, stratospheric ozone ($\mathrm{O3_{strat}}$), and tropospheric ozone ($\mathrm{O3_{trop}}$) to $\Delta\overline{u}$, respectively. Contours show the zonal mean zonal wind in the 1940-1955 period. The small black dots show where the response is statistically significant at the 95% confidence level.

Do the changes in the mean zonal wind due to ozone depletion imply an increase in the meridional flow? In the lower troposphere at mid-to-high latitudes the frictional force on the zonal wind balances the Coriolis force on the meridional flow, $r\overline{u} \approx f\overline{v}$, where $r$ is a drag constant and $f$ is the Coriolis parameter (cf. page 480 in Vallis, 2006). Note that eddy momentum fluxes do not appear in this balance as they are concentrated in the upper troposphere. This balance thus provides a link between ozone depletion and the meridional flow: the enhanced zonal wind at lower levels due to ozone depletion must be accompanied by an increase in the meridional wind as well. To demonstrate this balance, Fig. 7 shows the correlation between the DJF $\Delta f\overline{v}$ and $\Delta\overline{u}$ averaged over the lower troposphere (600 hPa to surface) and over mid-high latitudes ($50°\mathrm{S} - 70°\mathrm{S}$) across the four ensembles. Changes in $f\overline{v}$ are very highly correlated with changes in $\overline{u}$, with $r = 0.99$ in the All ensemble (red dots), $r = 0.98$ for Fix-ODS (blue dots), $r = 0.99$ for $\mathrm{Fix\text{-}ODS\&O3_{strat}}$ (green dots) and $r = 0.94$ for Fix-O3 (purple dots). Not only is there an excellent correlation between $\Delta f\overline{v}$ and $\Delta\overline{u}$, but ensembles with ozone depletion (All and Fix-ODS) show a larger increase in the mean zonal and meridional winds, in contrast to ensembles with fixed stratospheric ozone ($\mathrm{Fix\text{-}ODS\&O3_{strat}}$ and Fix-

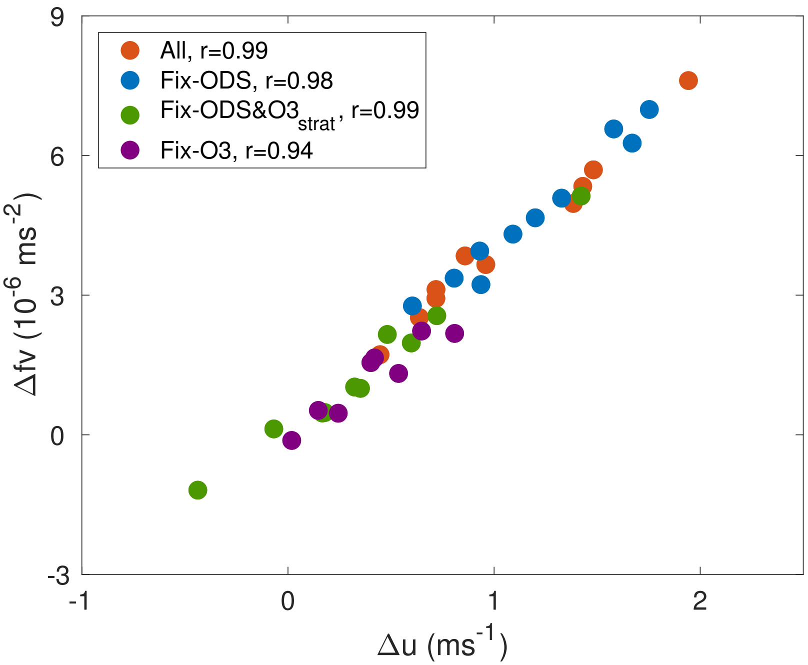

**Figure 7.** The response over the second half of the 20th century forcing of the DJF lower troposphere mid-high latitude Coriolis force on the meridional flow ($\Delta fv$) as a function of the mean zonal wind ($\Delta u$) in the full forcing ensemble (All, red), fixed ODS ensemble (Fix-ODS, blue), fixed ODS and stratospheric ozone ensemble ($\mathrm{Fix\text{-}ODS\&O3_{strat}}$, green) and fixed stratospheric and tropospheric ozone ensemble (Fix-O3, purple). Correlations appear at the upper left corner.

O3). Thus, the enhanced meridional flow in the All ensemble, and the associated increase in $\overline{P} - \overline{E}$, are largely due to the depletion of stratospheric ozone.

Changes in the mean zonal wind not only explain the increase in the mean meridional wind, but can be directly linked to the increase in the eddy moisture flux. Midlatitude eddies are driven by baroclinic instability (which arises from the vertical shear of the zonal wind, and the accompanying meridional temperature gradient), and thus the stronger increase of the mid-high latitudes ($50°\mathrm{S} - 70°\mathrm{S}$) mean zonal wind due to ozone depletion at upper levels relative to lower levels (i.e., an increase in the vertical shear, Fig. 6) suggests a strengthening of the eddies. However, during summer, the weak meridional temperature gradient might be insufficient to excite baroclinic eddies, and thus barotropic instability (which stems from the relative vorticity gradient, $u_{yy}$, where the y subscript represents the meridional derivative) might also be a driver of the midlatitude eddies.

To examine which instability drives the increase in eddy moisture flux, in Fig. 8 we show the correlation between the vertically integrated $\Delta\overline{v'q'}$ (the eddy moisture flux) and $\Delta\overline{u_z}$ (the vertical shear of the zonal wind, panel a) and the vertically averaged **(through the entire atmosphere)** $\Delta\overline{u_{yy}}$ (the curvature of the zonal winds, which is associated with barotropic instability, panel b). For simplicity, we define $\overline{u_z}$ as the zonal wind difference between upper (300 hPa-500 hPa) and lower

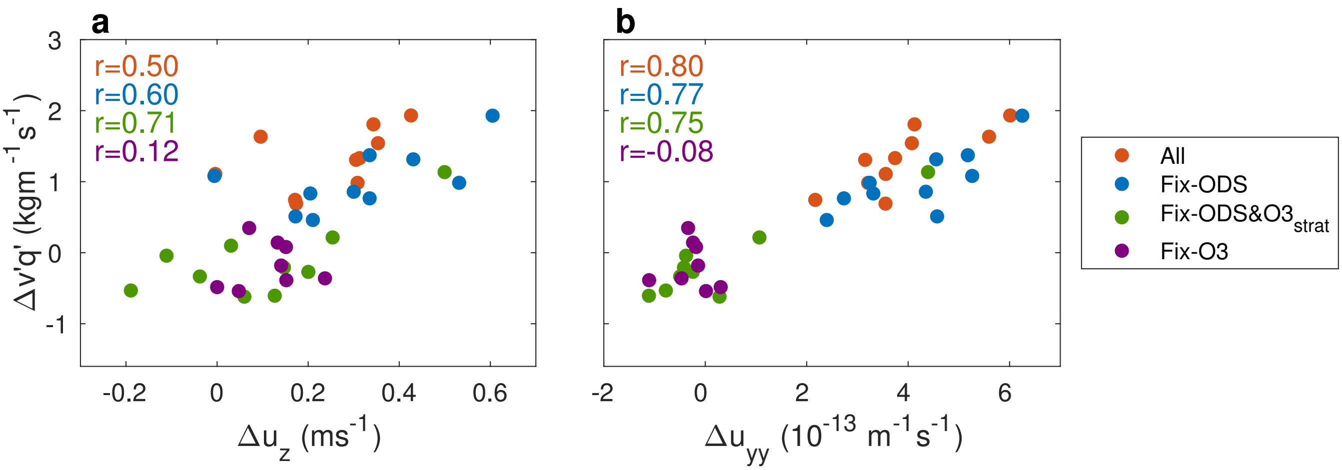

**Figure 8.** The response over the second half of the 20th century forcing of the DJF mid-high latitude eddy moisture flux ($\Delta\overline{v'q'}$) as a function of (a) the vertical shear of the zonal wind ($\Delta u_z$), and (b) the meridional gradient of the mean relative vorticity ($\Delta u_{yy}$) in the full forcing ensemble (All, red), fixed ODS ensemble (Fix-ODS, blue), fixed ODS and stratospheric ozone ensemble (Fix-ODS&O3$_{\mathrm{strat}}$, green) and fixed stratospheric and tropospheric ozone ensemble (Fix-O3, purple). Correlations appear at the upper left corner of each panel.

(600 hPa-**850 hPa**) levels. All variables are averaged over mid-high latitudes ($50°\mathrm{S} - 70°\mathrm{S}$). We use here the absolute value of $\overline{v'q'}$ so that the positive values of $\Delta\overline{v'q'}$ indicate strengthening of the eddy moisture flux onto the Antarctic continent.

As seen in Fig. 8, $\Delta\overline{v'q'}$ has a modest correlation with $\Delta\overline{u_z}$ across most ensembles ($r = 0.50$ in All, $r = 0.60$ in Fix-ODS, $r = 0.71$ in Fix-ODS&O3$_{\mathrm{strat}}$ and $r = 0.12$ in Fix-O3). More importantly, ensembles with ozone depletion (red and blue dots) do not show a significantly larger increase in $\overline{u_z}$ relative to ensembles with fixed stratospheric ozone (purple and green dots): ozone depletion thus has a weak impact on DJF $\overline{u_z}$. In contrast, $\Delta\overline{v'q'}$ has a higher correlation with $\Delta\overline{u_{yy}}$ across most ensembles ($r = 0.80$ in All, $r = 0.77$ in Fix-ODS, $r = 0.75$ in Fix-ODS&O3$_{\mathrm{strat}}$ and $r = -0.08$ in Fix-O3), and ensembles with ozone depletion (red and blue dots) do show a significant increase in $\overline{u_{yy}}$ relative to ensembles with fixed stratospheric ozone (purple and green dots). This analysis suggests that increased barotropic instability is the primary mechanism via which ozone depletion enhances the eddy-moisture flux, resulting in a larger Antarctic SMB over the second half of the 20th century.

## 5 Conclusions

Two recent studies have suggested that increasing ozone depleting substances (ODS) and the accompanying loss of stratospheric ozone have caused a substantial fraction of the increase in Antarctic surface mass balance over the second half of the 20th century. Neither study, however, cleanly separated these forcings. We here quantified the separate contribution of these forcing agents in increasing the Antarctic SMB, using fixed-forcing ensembles of model simulations. Our results show that ODS and stratospheric ozone have had comparable effects on the annual mean Antarctic SMB, and together account for $\sim 40\%$ of the SMB increase over the second half of the 20th century. The effect of stratospheric ozone are especially pronounced during Austral summer, when they account for $\sim 60\%$ of the SMB increase.

We have also **shown** that ozone depletion affects the SMB by enhancing the meridional circulation (mean and eddies), thus converging more water vapor over the Antarctic continent, and leading to increases in snowfall. The enhanced meridional flow is linked to ozone depletion through changes in the mean zonal wind. Specifically, in the lower troposphere, a stronger mean zonal wind at mid-high latitudes is balanced by a stronger mean meridional wind. Additionally, increases in the meridional gradient of the **zonal** mean relative vorticity, due to ozone-induced zonal wind changes, enhances barotropic instability, and leads to increases in meridional eddy moisture fluxes.

Our results have confirmed that ODS and the accompanying depletion of stratospheric ozone have substantially contributed to the recent increases in Antarctic SMB and, therefore, the phase out of ODS by the Montreal Protocol, and the accompanying recovery of stratospheric ozone, will act to decrease the SMB over the next several decades. The effect of ODS reduction and ozone recovery on the SMB will thus oppose the effect of increasing greenhouse gases, particularly during Austral summer. This has implications for the emergence/identification of SMB increases in observations, i.e., not only could this emergence be delayed (or masked) by natural variability (Previdi and Polvani, 2016), but will also be delayed as a consequence of the Montreal Protocol (Polvani et al., 2011a; Barnes et al., 2014).

*Code and data availability.* Data and codes are available upon request from: rc3101@colubia.edu

*Author contributions.* RC analyzed the data, MRE conducted the runs, and together with MP and LMP discussed and wrote the manuscript.

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

*Acknowledgements.* We acknowledge the CESM Large Ensemble Community Project and supercomputing resources provided by NSF/CISL/Yellowstone. This research is founded by a grant from the National Science Foundation to Columbia University.

## References

Agosta, C., Amory, C., Kittel, C., Orsi, A., Favier, V., Gallée, H., van den Broeke, M. R., Lenaerts, J. T. M., Melchior van Wessem, J., van de Berg, W. J., and Fettweis, X.: Estimation of the Antarctic surface mass balance using the regional climate model MAR (1979-2015) and identification of dominant processes, The Cryosphere, 13, 281–296, 2019.

Barnes, E. A., Barnes, N. W., and Polvani, L. M.: Delayed Southern Hemisphere Climate Change Induced by Stratospheric Ozone Recovery, as Projected by the CMIP5 Models, J. Climate, 27, 852–867, 2014.

Cataldo, M., Evangelista, H., Simões, J. C., Godoi, R. H. M., Simmonds, I., Hollanda, M. H., Wainer, I., Aquino, F., and Van Grieken, R.: Mineral dust variability in central West Antarctica associated with ozone depletion, Atmos. Chem. Phys., 13, 2165–2175, 2013.

England, M. R., Polvani, L. M., Smith, K. L., Landrum, L., and Holland, M. M.: Robust response of the Amundsen Sea Low to stratospheric ozone depletion, Geophys. Res. Lett., 43, 8207–8213, 2016.

Fretwell, P., Pritchard, H. D., Vaughan, D. G., Bamber, J. L., Barrand, N. E., Bell, R., Bianchi, C., Bingham, R. G., Blankenship, D. D., Casassa, G., Catania, G., Callens, D., Conway, H., Cook, A. J., Corr, H. F. J., Damaske, D., Damm, V., Ferraccioli, F., Forsberg, R., Fujita, S., Gim, Y., Gogineni, P., Griggs, J. A., Hindmarsh, R. C. A., Holmlund, P., Holt, J. W., Jacobel, R. W., Jenkins, A., Jokat, W., Jordan, T., King, E. C., Kohler, J., Krabill, W., Riger-Kusk, M., Langley, K. A., Leitchenkov, G., Leuschen, C., Luyendyk, B. P., Matsuoka, K., Mouginot, J., Nitsche, F. O., Nogi, Y., Nost, O. A., Popov, S. V., Rignot, E., Rippin, D. M., Rivera, A., Roberts, J., Ross, N., Siegert, M. J., Smith, A. M., Steinhage, D., Studinger, M., Sun, B., Tinto, B. K., Welch, B. C., Wilson, D., Young, D. A., Xiangbin, C., and Zirizzotti, A.: Bedmap2: improved ice bed, surface and thickness datasets for Antarctica, The Cryosphere, 7, 375–393, 2013.

Frezzotti, M., Scarchilli, C., Becagli, S., Proposito, M., and Urbini, S.: A synthesis of the Antarctic surface mass balance during the last 800 yr, The Cryosphere, 7, 303–319, 2013.

Frieler, K., Clark, P. U., He, F., Buizert, C., Reese, R., Ligtenberg, S. R. M., van den Broeke, M. R., Winkelmann, R., and Levermann, A.: Consistent evidence of increasing Antarctic accumulation with warming, Nature Climate Change, 5, 348–352, 2015.

Golledge, N. R.: Long-term projections of sea-level rise from ice sheets, Wiley Interdiscip. Rev.: Climate Change, 11, e634, 2020.

Grieger, J., Leckebusch, G. C., Raible, C. C., Rudeva, I., and Simmonds, I.: Subantarctic cyclones identified by 14 tracking methods, and their role for moisture transports into the continent, Tellus, 70, 1454 808, 2018.

Hurrell, J. W., Holland, M. M., Gent, P. R., Ghan, S., Kay, J. E., Kushner, P. J., Lamarque, J.-F., Large, W. G., Lawrence, D., Lindsay, K., Lipscomb, W. H., Long, M. C., Mahowald, N., Marsh, D. R., Neale, R. B., Rasch, P., Vavrus, S., Vertenstein, M., Bader, D., Collins, W. D., Hack, J. J., Kiehl, J., and Marshall, S.: The Community Earth System Model: A Framework for Collaborative Research, Bull. Am. Meteor. Soc., 94, 1339–1360, 2013.

IPCC: Climate Change 2013: The Physical Science Basis, Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, eds Stocker T. F. et al., Cambridge University Press, 2013.

Kay, J. E., Deser, C., Phillips, A., Mai, A., Hannay, C., Strand, G., Arblaster, J. M., Bates, S. C., Danabasoglu, G., Edwards, J., Holland, M., Kushner, P., Lamarque, J.-F., Lawrence, D., Lindsay, K., Middleton, A., Munoz, E., Neale, R., Oleson, K., Polvani, L., and Vertenstein, M.: The Community Earth System Model (CESM) Large Ensemble Project: A Community Resource for Studying Climate Change in the Presence of Internal Climate Variability, Bull. Am. Meteor. Soc., 96, 1333–1349, 2015.

Krinner, G., Magand, O., Simmonds, I., Genthon, C., and Dufresne, J. L.: Simulated Antarctic precipitation and surface mass balance at the end of the twentieth and twenty-first centuries, Clim. Dyn., 28, 215–230, 2007.

Landrum, L. L., Holland, M. M., Raphael, M. N., and Polvani, L. M.: Stratospheric Ozone Depletion: An Unlikely Driver of the Regional Trends in Antarctic Sea Ice in Austral Fall in the Late Twentieth Century, Geophys. Res. Lett., 44, 11,062–11,070, 2017.

Lenaerts, J. T. M., van den Broeke, M. R., van de Berg, W. J., van Meijgaard, E., and Kuipers Munneke, P.: A new, high-resolution surface mass balance map of Antarctica (1979-2010) based on regional atmospheric climate modeling, Geophys. Res. Lett., 39, L04501, 2012.

Lenaerts, J. T. M., Fyke, J., and Medley, B.: The Signature of Ozone Depletion in Recent Antarctic Precipitation Change: A Study With the Community Earth System Model, Geophys. Res. Lett., 45, 12,931–12,939, 2018.

Levermann, A., Winkelmann, R., Albrecht, T., Goelzer, H., Golledge, N. R., Greve, R., Huybrechts, P., Jordan, J., Leguy, G., Martin, D., Morlighem, M., Pattyn, F., Pollard, D., Quiquet, A., Rodehacke, C., Seroussi, H., Sutter, J., Zhang, T., Van Breedam, J., Calov, R., DeConto, R., Dumas, C., Garbe, J., Hilmar Gudmundsson, G., Hoffman, M. J., Humbert, A., Kleiner, T., Lipscomb, W. H., Meinshausen, M., Ng, E., Nowicki, S. M. J., Perego, M., Price, S. F., Saito, F., Schlegel, N., Sun, S., and van de Wal, R. S. W.: 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, 35–76, 2020.

Ligtenberg, S. R. M., van de Berg, W. J., van den Broeke, M. R., Rae, J. G. L., and van Meijgaard, E.: Future surface mass balance of the Antarctic ice sheet and its influence on sea level change, simulated by a regional atmospheric climate model, Clim. Dyn., 41, 867–884, 2013.

Monaghan, A. J., Bromwich, D. H., Fogt, R. L., Wang, S., Mayewski, P. A., Dixon, D. A., Ekaykin, A., Frezzotti, M., Goodwin, I., Isaksson, E., Kaspari, S. D., Morgan, V. I., Oerter, H., Van Ommen, T. D., Van der Veen, C. J., and Wen, J.: Insignificant Change in Antarctic Snowfall Since the International Geophysical Year, Science, 313, 827–831, 2006a.

Monaghan, A. J., Bromwich, D. H., and Wang, S.: Recent trends in Antarctic snow accumulation from Polar MM5 simulations, Philos. Trans. Roy. Soc. London A, 364, 1683–1708, 2006b.

Monaghan, A. J., Bromwich, D. H., and Schneider, D. P.: Twentieth century Antarctic air temperature and snowfall simulations by IPCC climate models, Geophys. Res. Lett., 35, L07502, 2008.

Palerme, C., Genthon, C., Claud, C., Kay, J. E., Wood, N. B., and L'Ecuyer, T.: Evaluation of current and projected Antarctic precipitation in CMIP5 models, Clim. Dyn., 48, 225–239, 2017.

Papritz, L., Pfahl, S., Rudeva, I., Simmonds, I., Sodemann, H., and Wernli, H.: The Role of Extratropical Cyclones and Fronts for Southern Ocean Freshwater Fluxes, J. Climate, 27, 6205–6224, 2014.

Polvani, L. M., Previdi, M., and Deser, C.: Large cancellation, due to ozone recovery, of future Southern Hemisphere atmospheric circulation trends, Geophys. Res. Lett., 38, L04707, 2011a.

Polvani, L. M., Waugh, D. W., Correa, G. J. P., and Son, S. W.: Stratospheric Ozone Depletion: The Main Driver of Twentieth-Century Atmospheric Circulation Changes in the Southern Hemisphere, J. Climate, 24, 795–812, 2011b.

Polvani, L. M., Previdi, M., England, M. R., Chiodo, G., and Smith, K. L.: Substantial twentieth-century Arctic warming caused by ozone-depleting substances, Nature Climate Change, 10, 130–133, 2020.

Previdi, M. and Polvani, L. M.: Climate system response to stratospheric ozone depletion and recovery, Q. J. R. Meteorol. Soc., 140, 2401–2419, 2014.

Previdi, M. and Polvani, L. M.: Anthropogenic impact on Antarctic surface mass balance, currently masked by natural variability, to emerge by mid-century, Env. Res. Lett., 11, 094001, 2016.

Previdi, M. and Polvani, L. M.: Impact of the Montreal Protocol on Antarctic Surface Mass Balance and Implications for Global Sea Level Rise, J. Climate, 30, 7247–7253, 2017.

Rignot, E., Casassa, G., Gogineni, P., Krabill, W., Rivera, A., and Thomas, R.: Accelerated ice discharge from the Antarctic Peninsula following the collapse of Larsen B ice shelf, Geophys. Res. Lett., 31, L18401, 2004.

Rignot, E., Mouginot, J., Scheuchl, B., van den Broeke, M., van Wessem, M. J., and Morlighem, M.: Four decades of Antarctic Ice Sheet mass balance from 1979-2017, Proc. Natl. Acad. Sci. U.S.A., 116, 1095–1103, 2019.

Seager, R., Naik, N., and Vecchi, G. A.: Thermodynamic and Dynamic Mechanisms for Large-Scale Changes in the Hydrological Cycle in Response to Global Warming, J. Climate, 23, 4651–4668, 2010.

Shepherd, A., Ivins, E. R., Geruo, A., Barletta, V. R., Bentley, M. J., Bettadpur, S., Briggs, K. H., Bromwich, D. H., Forsberg, R., Galin, N., Horwath, M., Jacobs, S., Joughin, I., King, M. A., Lenaerts, J. T. M., Li, J., Ligtenberg, S. R. M., Luckman, A., Luthcke, S. B., McMillan, M., Meister, R., Milne, G., Mouginot, J., Muir, A., Nicolas, J. P., Paden, J., Payne, A. J., Pritchard, H., Rignot, E., Rott, H., Sørensen, L. S., Scambos, T. A., Scheuchl, B., Schrama, E. J. O., Smith, B., Sundal, A. V., van Angelen, J. H., van de Berg, W. J., van den Broeke, M. R., Vaughan, D. G., Velicogna, I., Wahr, J., Whitehouse, P. L., Wingham, D. J., Yi, D., Young, D., and Zwally, H. J.: A Reconciled Estimate of Ice-Sheet Mass Balance, Science, 338, 1183, https://doi.org/10.1126/science.1228102, 2012.

Taylor, K. E., Stouffer, R. J., and Meehl, G. A.: An Overview of CMIP5 and the Experiment Design, Bull. Am. Meteor. Soc., 93, 485–498, 2012.

Trenberth, K. E. and Guillemot, C. J.: Evaluation of the Global Atmospheric Moisture Budget as Seen from Analyses., J. Climate, 8, 2255–2280, 1995.

Uotila, P., Lynch, A. H., Cassano, J. J., and Cullather, R. I.: Changes in Antarctic net precipitation in the 21st century based on Intergovernmental Panel on Climate Change (IPCC) model scenarios, J. Geophys. Res., 112, D10107, 2007.

Vallis, G. K.: Atmospheric and Oceanic Fluid Dynamics, pp. 770. Cambridge University Press, Cambridge, U.K., 2006.

Velicogna, I., Sutterley, T. C., and van den Broeke, M. R.: Regional acceleration in ice mass loss from Greenland and Antarctica using GRACE time-variable gravity data, Geophys. Res. Lett., 41, 8130–8137, 2014.

Wouters, B., Martin-Español, A., Helm, V., Flament, T., van Wessem, J. M., Ligtenberg, S. R. M., van den Broeke, M. R., and Bamber, J. L.: Dynamic thinning of glaciers on the Southern Antarctic Peninsula, Science, 348, 899–903, 2015.