Impact of the Montreal Protocol on Antarctic Surface Mass Balance and Implications for Global Sea Level Rise

MICHAEL PREVIDI

Lamont-Doherty Earth Observatory, Columbia University, Palisades, New York

LORENZO M. POLVANI

Lamont-Doherty Earth Observatory, Columbia University, Palisades, and Department of Applied Physics and Applied Mathematics, and Department of Earth and Environmental Sciences, Columbia University, New York, New York

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ABSTRACT

The Montreal Protocol on Substances that Deplete the Ozone Layer, adopted in 1987, is an international treaty designed to protect the ozone layer by phasing out emissions of chlorofluorocarbons and other ozone-depleting substances (ODSs). A growing body of scientific evidence now suggests that the implementation of the Montreal Protocol will have significant effects on climate over the next several decades, both by enabling stratospheric ozone recovery and by decreasing atmospheric concentrations of ODSs, which are greenhouse gases. Here, using a state-of-the-art chemistry–climate model, the Community Earth System Model (Whole Atmosphere Community Climate Model) [CESM(WACCM)], it is shown that the Montreal Protocol, through its impact on atmospheric ODS concentrations, leads to a substantial decrease in Antarctic surface mass balance (SMB) over the period 2006–65 relative to a hypothetical "World Avoided" scenario in which the Montreal Protocol has not been implemented. This SMB decrease produces an additional 25 mm of global sea level rise (GSLR) by the year 2065 relative to the present day. It is found, however, that the additional GSLR resulting from the relative decrease in Antarctic SMB is more than offset by a reduction in ocean thermal expansion, leading to a net mitigation of future GSLR due to the Montreal Protocol.

1. Introduction

The Montreal Protocol was born over concerns that increasing levels of surface ultraviolet (UV) radiation resulting from stratospheric ozone depletion would be detrimental to human health, agriculture, and natural ecosystems (United Nations Environment Programme 2017). What was not fully appreciated at the time the treaty was adopted, however, were the potential impacts that it would have on climate. These impacts are directly tied to the phaseout of ozone-depleting substance (ODS) emissions stipulated by the Montreal Protocol and its amendments, along with the ensuing decrease in atmospheric ODS concentrations. On the one hand, this is anticipated to lead to the recovery of stratospheric ozone over the next several decades (WMO 2014), with a number of associated climatic effects expected (Previdi and Polvani 2014). Additionally, since ODSs are greenhouse gases (GHGs), the decrease in their atmospheric concentrations due to the Montreal Protocol substantially reduces the global-mean radiative forcing (Velders et al. 2007; see also Fig. 1a), with implications for surface temperature (Garcia et al. 2012), the hydrological cycle (Wu et al. 2013), and the potential intensity of tropical cyclones (Polvani et al. 2016). Here, we show for the first time that this reduced radiative forcing is also likely to have a large effect on the surface mass balance (SMB) of Antarctica over the next several decades.

2. Methods

a. Model and experiments

The current work employs the Community Earth System Model (Whole Atmosphere Community Climate Model) [CESM(WACCM); Marsh et al. 2013], a

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Corresponding author: Dr. Michael Previdi, mprevidi@ldeo.columbia.edu

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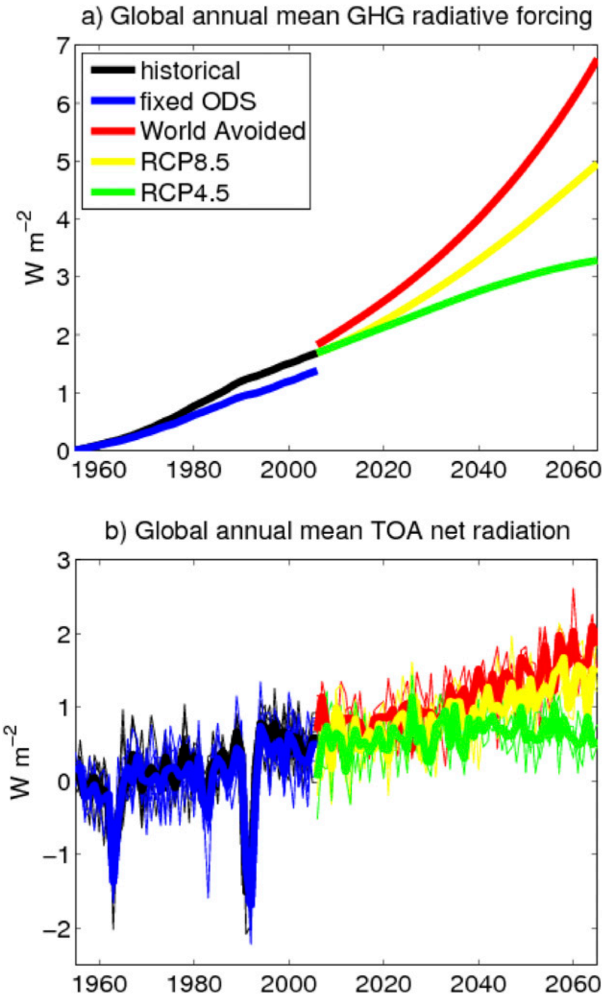

FIG. 1. (a) Global annual mean radiative forcing (relative to 1955) as a result of well-mixed GHGs in the CESM(WACCM) experiments. (b) Global annual mean TOA net radiation in the CESM(WACCM) experiments, with thin and thick curves representing individual ensemble members and ensemble means, respectively. All time series are referenced to 1955 by removing the historical experiment ensemble mean TOA radiation for that year.

fully coupled atmosphere–ocean general circulation model (GCM) with sea ice and land surface components. The atmospheric component of the coupled model is version 4 of WACCM, a "high top" chemistry–climate model that includes the same physical parameterizations as the Community Atmosphere Model, version 4 (CAM4; Neale et al. 2013). WACCM has a horizontal resolution of 1.9° latitude × 2.5° longitude, with 66 vertical levels extending to an altitude of approximately 140 km. It includes a fully interactive stratospheric chemistry module based on version 3 of the Model for Ozone and Related Chemical Tracers (MOZART; Kinnison et al. 2007), which allows for a realistic simulation of the chemical effects of ODSs on stratospheric ozone (Marsh et al. 2013). WACCM is coupled to the Community Land Model, version 4 (CLM4; Lawrence et al. 2011), and the Parallel Ocean Program (POP) is the ocean GCM with dynamic–thermodynamic sea ice (Danabasoglu et al. 2012; Holland et al. 2012). CLM4 and WACCM share a common horizontal grid, as do the ocean and sea ice components, which employ a nominal 1° latitude–longitude resolution.

We consider a total of five CESM(WACCM) experiments, referred to herein as historical, fixed ODS, representative concentration pathways 4.5 and 8.5 (RCP4.5 and RCP8.5), and the "World Avoided." The historical and fixed ODS experiments cover the period 1955–2005, with each experiment including six individual ensemble members differing only in their initial conditions. The RCP4.5, RCP8.5, and World Avoided experiments cover the 2005–65 period and include three ensemble members each.

We leverage the existing historical simulations with CESM(WACCM) that were performed for phase 5 of the Coupled Model Intercomparison Project (CMIP5; Taylor et al. 2012), in which the model is driven by observed time-varying changes in all natural and anthropogenic forcings. For comparison with these simulations, we carried out a set of fixed ODS runs that are identical to the historical simulations except for the prescribed surface concentrations of ODSs, which are held fixed at 1955 levels. Holding ODSs fixed has a sizable impact on the global-mean GHG radiative forcing, reducing this forcing by 0.3 W m^{-2} (18%) by the year 2005 (Fig. 1a and Table 1).

The RCP4.5 and RCP8.5 simulations that we analyze are similarly the ones that were performed for CMIP5. These simulations include projected changes in the atmospheric concentrations of non-ODS GHGs (CO_2, CH_4, and N_2O) and anthropogenic aerosols and, importantly, decreases in atmospheric ODSs due to the Montreal Protocol and its amendments (with the latter based on the adjusted SRES A1 scenario from the World Meteorological Organization; WMO 2007). Finally, we carried out a set of World Avoided simulations in order to examine the impact of unmitigated growth in atmospheric ODSs (see Table 1 for a list of the ODSs considered). These simulations follow a scenario (Garcia et al. 2012) in which the surface ODS concentrations that are input to the model increase at a rate of 3.5% yr^{-1} beginning in 1985, under the assumption that the Montreal Protocol does not exist. All other imposed forcings in the World Avoided simulations are identical to those in RCP4.5. Figure 1a indicates that the unchecked growth of atmospheric ODSs in the World Avoided results in a substantial GHG radiative forcing

TABLE 1. Anthropogenic ODSs in CESM(WACCM). Global and annual mean radiative forcing ($W\,m^{-2}$) is relative to 1955. (CFC is chlorofluorocarbon, and HCFC is hydrochlorofluorocarbon.)

Species	Chemical formula	Forcing in 2005 (historical)	Forcing in 2065 (World Avoided)	Forcing in 2065 (RCP4.5[a])
CFC-11	CCl_3F	0.063	0.86	0.019
CFC-12	CCl_2F,	0.17	1.9	0.088
CFC-113	CCl_2FCClF_2	0.023	0.21	0.010
CFC-114[b]	$CClF_2CClF_2$	—	—	—
CFC-115[b]	$CClFCF_3$	—	—	—
Carbon tetrachloride	CCl_4	0.0069	0.27	−0.0044
Methyl chloroform	CH_3CCl_3	0.0013	0.12	-1.5×10^{-6}
HCFC-22	$GHClF_2$	0.032	0.20	0.014
HCFC-142b[b]	CH_3CCl_2F	—	—	—
Halon-1211	$CBrClF_2$	0.0013	0.0061	1.1×10^{-4}
Halon-2402[b]	$CBrF_2CBrF_2$	—	—	—
Methyl bromide	CH_3Br	8.2×10^{-6}	5.5×10^{-4}	-9.4×10^{-4}
Halon-1202[b]	CBr_2F_2	—	—	—
Halon-1301	$CBrF_3$	9.3×10^{-4}	0.0031	5.5×10^{-4}

[a] ODS forcing nearly identical in RCP8.5.

[b] Not computed explicitly in the model, but effect is taken into account by adjusting stoichiometrically the mixing ratio of the species listed immediately above, which has a similar loss rate profile (Garcia et al. 2012).

of 6.8 $W\,m^{-2}$ by 2065 (see also Garcia et al. 2012), which is about a factor of 2 larger than the forcing in RCP4.5 (3.3 $W\,m^{-2}$ in 2065). The forcing in the World Avoided is even considerably larger than under the so-called business-as-usual RCP8.5 scenario (yellow curve in Fig. 1a), which is at the upper end of the future scenarios considered by the Intergovernmental Panel on Climate Change (IPCC; Myhre et al. 2013).

b. *Quantification of greenhouse gas forcing*

We estimate the global and annual mean radiative forcing due to well-mixed GHGs in the CESM(WACCM) experiments (see Fig. 1a) as follows. For the historical, RCP4.5, and RCP8.5 scenarios, we use published estimates (Meinshausen et al. 2011) of the stratosphere-adjusted forcing that are provided by the Potsdam Institute for Climate Impact Research (available for download at http://www.pik-potsdam.de/~mmalte/rcps/index.htm#Download). Forcing time series were acquired for each individual GHG represented in our model (including all ODSs), and these individual time series were summed to obtain the total GHG forcing. To estimate the forcing in the fixed ODS experiment, we subtract the ODS forcing from the total GHG forcing in the historical experiment. Last, the total GHG forcing in the World Avoided experiment is estimated by first computing the forcing time series for each individual ODS. This is accomplished by multiplying the prescribed time-varying change in ODS concentration (in ppb) by the radiative efficiency of the ODS (in $W\,m^{-2}\,ppb^{-1}$) as reported in the IPCC Fifth Assessment Report (Myhre et al. 2013). The individual ODS forcings computed in this manner are then added to the non-ODS GHG forcing from RCP4.5 to obtain the total forcing in the World Avoided experiment.

3. Results

a. *Simulated Antarctic SMB changes*

We begin our assessment of Antarctic SMB (defined herein as precipitation minus evaporation/sublimation) by considering the simulated SMB changes in the historical and fixed ODS experiments, as shown in Fig. 2a. There is a clear SMB increase in both experiments over the 1956–2005 period, with this increase being noticeably more pronounced in the historical simulations. In the ensemble mean, the 1956–2005 SMB increase is found to be 375 $Gt\,yr^{-1}$ in the historical experiment and 158 $Gt\,yr^{-1}$ in the fixed ODS experiment based on linear trend analysis. The difference in the ensemble-mean SMB increase between the two experiments is statistically significant at the 95% confidence level based on the Student's t test. SMB increases in both experiments are driven almost entirely by increases in precipitation (snowfall), with evaporation/sublimation changes being much smaller in magnitude. It is worth noting that the simulated SMB increase in our historical and fixed ODS experiments is in qualitative agreement with results from other climate modeling studies (Krinner et al. 2007; Uotila et al. 2007; Monaghan et al. 2008; Ligtenberg et al. 2013; Frieler et al. 2015), indicating that the Antarctic SMB should increase in response to anthropogenic forcing. While observations from recent

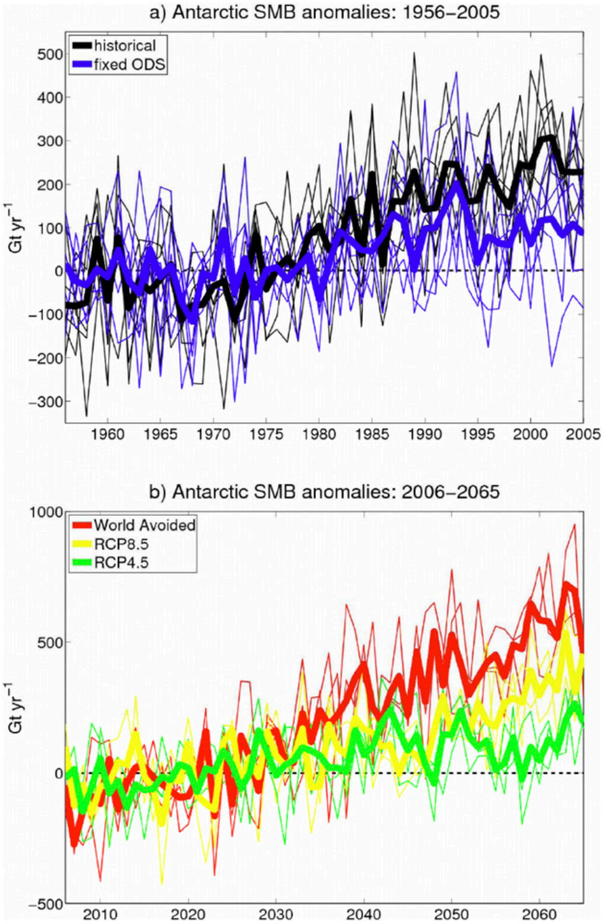

FIG. 2. Anomalies in model-simulated Antarctic SMB (integrated annually and over the grounded ice sheet) during (a) 1956–2005 and (b) 2006–65. SMB anomalies are relative to the first 30 years of each period. Thin curves represent individual ensemble members, while thick curves are the ensemble means.

decades do not show a significant increase in Antarctic SMB (Monaghan et al. 2006a,b; van den Broeke et al. 2006; Lenaerts et al. 2012), this does not necessarily imply that current climate models are fundamentally flawed: large natural variability may simply be masking the anthropogenically forced response (Previdi and Polvani 2016).

Our model results shown in Fig. 2a indicate that, over the period 1956–2005, holding atmospheric ODS concentrations fixed has a considerable impact on the simulated multidecadal trend in Antarctic SMB. In principle, a portion of this impact could occur through effects on stratospheric ozone, since ozone depletion is simulated by the model in the historical experiment but not in the fixed ODS experiment. Our analysis suggests, however, that stratospheric ozone effects on Antarctic SMB are likely to be relatively small. First of all, stratospheric ozone depletion occurs primarily during austral spring, with the associated climatic impacts at the surface and in the troposphere occurring mainly during summer (Thompson et al. 2011; Previdi and Polvani 2014). We find, though, that the ensemble-mean SMB increase in the historical experiment during 1956–2005 is larger than the corresponding increase in the fixed ODS experiment in all four seasons, with the difference between the two experiments being statistically significant (at the 95% confidence level based on the Student's t test) during summer and fall.

Second, many of the surface/tropospheric impacts of ozone depletion are mediated through forced changes in the atmospheric circulation, notably via changes in the so-called southern annular mode (SAM; Thompson et al. 2011; Previdi and Polvani 2014). We estimate the contribution of the SAM to the anomalous (i.e., historical minus fixed ODS) annual SMB trend (see, e.g., Previdi and Polvani 2014) as follows:

$$\left(\frac{d\mathrm{SMB}}{dt}\right)_{\mathrm{SAM}} = r_{\mathrm{SMB:SAM}} \times \left[\left(\frac{d\mathrm{SAM}}{dt}\right)_{\mathrm{hist}} - \left(\frac{d\mathrm{SAM}}{dt}\right)_{\mathrm{fixODS}}\right], \qquad (1)$$

where $r_{\mathrm{SMB:SAM}} = \partial\mathrm{SMB}/\partial\mathrm{SAM}$ is the linear regression coefficient quantifying the relationship between Antarctic SMB and the SAM and $(d\mathrm{SAM}/dt)_{\mathrm{hist}} - (d\mathrm{SAM}/dt)_{\mathrm{fixODS}}$ is the anomalous SAM trend, defined as the difference in the ensemble-mean SAM trend between the historical and fixed ODS experiments during 1956–2005. We compute $r_{\mathrm{SMB:SAM}}$ through ordinary least squares linear regression, using detrended annual time series of Antarctic SMB and the SAM index from each individual ensemble member in the historical and fixed ODS experiments. The SAM index is defined as the normalized zonal-mean sea level pressure difference between 40° and 65°S (Marshall 2003). The mean value of $r_{\mathrm{SMB:SAM}}$, averaged over all 12 ensemble members considered, is found to be $-33\,\mathrm{Gt\,yr^{-1}}$. Using this in Eq. (1), along with an anomalous SAM trend of $+0.006\,\mathrm{yr^{-1}}$, yields $(d\mathrm{SMB}/dt)_{\mathrm{SAM}} = -0.2\,\mathrm{Gt\,yr^{-2}}$. This SMB trend as a result of the SAM is much smaller in magnitude and opposite in sign to the actual anomalous SMB trend ($+4.4\,\mathrm{Gt\,yr^{-2}}$), clearly indicating that the latter cannot be explained by the SAM. Along with the lack of a strong seasonality in the anomalous SMB response, this implies that differences in stratospheric ozone are not the primary driver of the simulated SMB differences between historical and fixed ODS. The latter differences, therefore, must be principally due to the direct radiative effects of atmospheric ODSs.

Given the strong SMB response to ODS forcing over the historical period (Fig. 2a), we anticipate that the

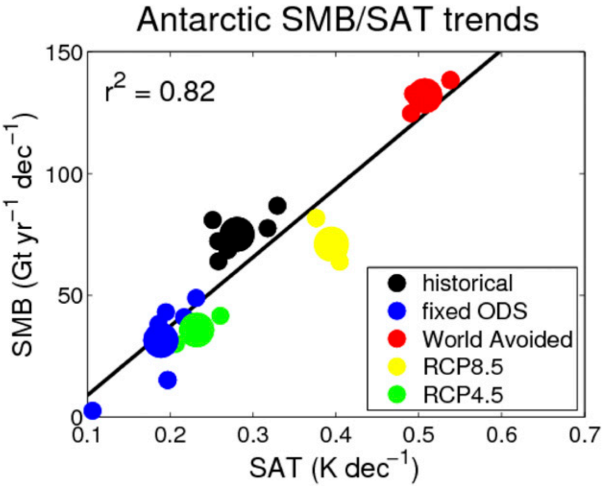

FIG. 3. Simulated trends in Antarctic SMB (Gt yr^{-1} decade^{-1}; integrated annually and over the grounded ice sheet) and SAT (K decade^{-1}; averaged annually and over the grounded ice sheet) in the various CESM(WACCM) experiments. Trends are computed over the 1956–2005 period in historical and fixed ODS and over the 2006–65 period in the World Avoided, RCP8.5, and RCP4.5. Small dots represent individual ensemble members, while large dots are the ensemble means. The black line is a least squares linear fit to the data.

mitigation of this forcing as a result of the Montreal Protocol will influence the temporal evolution of the SMB over the next several decades. Figure 2b indicates that this is indeed the case, with the pronounced differences in future SMB trends between the RCP4.5 simulations (green curves) and World Avoided simulations (red curves) reflecting the effect of the Montreal Protocol and its associated phaseout of ODS emissions. (Recall that the prescribed concentrations of non-ODS GHGs are identical in the RCP4.5 and World Avoided experiments.) By differencing the RCP4.5 and World Avoided ensemble-mean trends, we find that the Montreal Protocol reduces the 2006–65 SMB increase by 577 Gt yr^{-1} (from 792 Gt yr^{-1} in the World Avoided to 215 Gt yr^{-1} in RCP4.5). This relative decrease in SMB due to the Montreal Protocol is larger in magnitude than the ensemble-mean SMB increase of 426 Gt yr^{-1} that is simulated over the same time period under RCP8.5 (thick yellow curve in Fig. 2b).

The differences in simulated SMB trends between the various WACCM experiments discussed above are closely related to differences in the rate of Antarctic-mean warming, as illustrated in Fig. 3. Specifically, differences in Antarctic surface air temperature (SAT) trends between individual ensemble members are able to account for 82% of the variance in the simulated SMB trend. This SAT–SMB relationship exists because of the strong temperature dependence of the saturation vapor pressure, as given by the Clausius–Clapeyron equation. As a result of this dependence, greater rates of Antarctic warming are associated with larger increases in atmospheric moisture content, which drive larger increases in precipitation (snowfall) and thus SMB. A strong positive relationship between Antarctic SMB and temperature, such as occurs here in our model, is a robust feature of global warming simulations from climate models (Krinner et al. 2007; Uotila et al. 2007; Monaghan et al. 2008; Ligtenberg et al. 2013; Frieler et al. 2015; Previdi and Polvani 2016) and has been inferred as well from ice core data spanning the large temperature changes that occurred during the last deglaciation (Frieler et al. 2015).

Based on the preceding discussion, we conclude that the relative decrease in SMB due to the Montreal Protocol is essentially a thermodynamic response that simply follows from the reduced warming and moistening of the Antarctic atmosphere. The reduction in Antarctic warming, calculated from the difference in ensemble-mean SAT trends between the World Avoided and RCP4.5 experiments, totals 1.7 K over the 2006–65 period. This reduced warming is an expected consequence of the decrease in radiative forcing (Fig. 1a) resulting from a smaller atmospheric burden of ODSs. Note that the top-of-the-atmosphere (TOA) energy imbalance (reflecting the difference between radiative forcing and climate response) is larger in the World Avoided than in RCP4.5 (and RCP8.5) by the end of the simulations (Fig. 1b). This implies a greater amount of ''committed'' warming in the World Avoided and thus a larger-magnitude reduction in warming attributable to the Montreal Protocol when one considers longer time scales extending beyond 2065.

b. *Implications for global sea level rise*

The relative decrease in SMB due to the Montreal Protocol implies a positive contribution to future global sea level rise (GSLR) since less water mass will be stored in the form of snow and ice over Antarctica. Figure 4 indicates that this GSLR contribution from Antarctic SMB changes reaches +25 mm by 2065 (relative to 2006–35). However, since the implementation of the Montreal Protocol will result in less warming of the global ocean over the next several decades (not shown), ocean thermal expansion will correspondingly be reduced (Zickfeld et al. 2017), producing an opposite, mitigating effect on GSLR.

We calculate thermal expansion in our model from simulated changes in seawater potential density, using an approximation developed for Boussinesq ocean models (Smith et al. 2010; Griffies et al. 2014). Specifically, the global-mean steric sea level rise (essentially

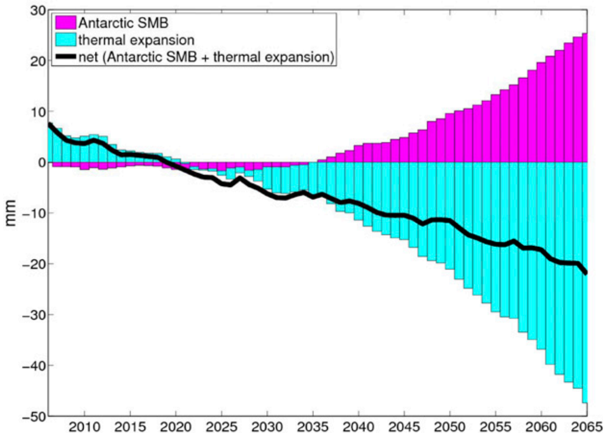

FIG. 4. Montreal Protocol contribution to global sea level rise during 2006–65, calculated based on the ensemble-mean difference between the RCP4.5 and World Avoided experiments. Global sea level rise is relative to the period 2006–35.

equivalent to thermal expansion) at time t is computed as follows:

$$\langle \eta_t \rangle = \langle H \rangle \left(\frac{\langle \rho_0 \rangle}{\langle \rho_t \rangle} - 1 \right), \tag{2}$$

where $\langle H \rangle$ is the mean ocean depth, $\langle \rho_0 \rangle$ is the initial global-mean in situ ocean density, and $\langle \rho_t \rangle$ is the global-mean in situ ocean density at time t. The global-mean in situ ocean density is defined as the ratio of total ocean mass to total ocean volume, with the latter assumed to remain constant. The total ocean mass is computed by integrating the seawater potential density over the depth of the water column and over the area of the global ocean. We account for drift in the model's preindustrial control simulation by removing the linear trend in global-mean steric sea level in the control simulation from all of the forced simulations.

We find that the Montreal Protocol's mitigating effect on GSLR as a result of reduced thermal expansion reaches −47 mm by 2065 (cyan bars in Fig. 4). This more than offsets the positive GSLR contribution from Antarctic SMB changes (+25 mm), yielding a net reduction in GSLR of −22 mm (black curve in Fig. 4). For comparison, in the World Avoided experiment, the ensemble-mean GSLR due to the combined effects of thermal expansion and Antarctic SMB increases is +81 mm in 2065. This indicates a substantial 27% reduction in future GSLR due to the Montreal Protocol.

Of course, future rates of GSLR will depend not only on thermal expansion and Antarctic SMB changes but also on other processes such as Antarctic dynamic mass loss and mass loss from Greenland and mountain glaciers (Church et al. 2013). While we are not able to quantify all of these additional GSLR contributions in WACCM (e.g., as a result of the lack of interactive ice sheets in the model), we can state with certainty that these additional contributions will be negative. In other words, by suppressing future warming, the Montreal Protocol will reduce Antarctic dynamic mass loss and mass loss from Greenland and mountain glaciers, thereby producing additional negative contributions to GSLR over the next several decades. This implies that the net reduction in GSLR of −22 mm that is cited above, which accounts only for effects on thermal expansion and Antarctic SMB, should be viewed as a lower bound on the mitigating potential of the Montreal Protocol.

4. Conclusions

Our results in this study clearly demonstrate that the Antarctic surface mass balance is likely to evolve very differently over the next several decades than it would have in the absence of the Montreal Protocol. This serves as a valuable lesson regarding the unintended consequences of environmental policy. In this case, these unintended consequences appear to be mainly beneficial (e.g., mitigation of future global sea level rise); however, this may not always be true (Robock 2008). Regardless of the relative costs and benefits, the Montreal Protocol has taught us that environmental policy can have far-reaching implications because of the interdependence of various components of the Earth system. It is critical to bear this in mind when making decisions about any proposed environmental policy going forward.

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