AGU PUBLICATIONS

Geophysical Research Letters

RESEARCH LETTER
10.1002/2014GL061627

Key Points:
- Climate trends in models depend on the input frequency of stratospheric ozone
- Zonal asymmetries in ozone do not solely cause biases in climate simulations
- Model simulations are greatly improved by specifying daily ozone values

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Citation:
Neely, R. R., III, D. R. Marsh, K. L. Smith, S. M. Davis, and L. M. Polvani (2014), Biases in southern hemisphere climate trends induced by coarsely specifying the temporal resolution of stratospheric ozone, *Geophys. Res. Lett.*, *41*, doi:10.1002/2014GL061627.

Received 25 AUG 2014
Accepted 15 OCT 2014
Accepted article online 20 OCT 2014

Biases in southern hemisphere climate trends induced by coarsely specifying the temporal resolution of stratospheric ozone

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Abstract Global climate models that do not include interactive middle atmosphere chemistry, such as most of those contributing to the Coupled Model Intercomparison Project Phase 5, typically specify stratospheric ozone using monthly mean, zonal mean values and linearly interpolate to the time resolution of the model. We show that this method leads to significant biases in the simulated climate of the southern hemisphere (SH) over the late twentieth century. Previous studies have attributed similar biases in simulated SH climate change to the effect of the spatial smoothing of the specified ozone, i.e., to using zonal mean concentrations. We here show that the bias in climate trends due to undersampling of the rapid temporal changes in ozone during the seasonal evolution of the Antarctic ozone hole is considerable and reaches all the way into the troposphere. Our results suggest that the bias can be substantially reduced by specifying daily ozone concentrations.

1. Introduction

Stratospheric ozone depletion is a major driver of changes in the southern hemisphere (SH) climate during the latter half of the twentieth century [*Thompson and Solomon*, 2002; *Gillett and Thompson*, 2003; *Perlwitz et al*., 2008; *Son et al*., 2008, 2009, 2010; *Polvani et al*., 2011a, 2011b; *Mclandress et al*., 2011; *Lee and Feldstein*, 2013]. Specifically, both observational [*Lee and Feldstein*, 2013] and modeling [*Polvani et al*., 2011a, 2011b] studies find that SH stratospheric ozone depletion during the late twentieth century has contributed upward of twice as much as the increase in greenhouse gases to the poleward shift of the SH westerly jet and the associated changes in SH precipitation in austral summer [*Kang et al*., 2011].

A good number of the climate models that contributed to the Coupled Model Intercomparison Project Phase 5 (CMIP5) now include a well-resolved stratospheric circulation [*Charlton-Perez et al*., 2013], and some include interactive stratospheric chemistry [*Eyring et al*., 2013]. However, the computational burden of coupled chemistry calculations can be prohibitive for long climate integrations, especially with increasing horizontal resolution; therefore, most models still specify the concentration of ozone, whence shortwave heating is computed [*Taylor et al*., 2012]. In such models, accurately representing the ozone hole is essential for capturing changes in SH climate over the late twentieth century and into the future [*Calvo et al*., 2012; *Young et al*., 2013].

Previous studies [*Crook et al*., 2008; *Gillett et al*., 2009; *Waugh et al*., 2009] have identified significant differences in atmospheric circulation between climate models forced with specified monthly mean, zonal mean ozone, as was used in CMIP5 [*Cionni et al*., 2011], and climate models with interactive stratospheric ozone chemistry. These studies show a weaker and warmer SH polar vortex when monthly mean, zonal mean ozone is specified and attribute this difference to the spatial smoothing associated with creating the zonal mean. However, these studies did not address the impact of specifying monthly mean ozone.

We here show that coarse (i.e., monthly) temporal smoothing leads to significant underestimate of the magnitude of ozone depletion. This bias is directly attributable to the linear time interpolation between the specified monthly values, which results in ozone holes that are not as deep as observed. We find that simulations with stratospheric ozone specified at monthly resolution (and interpolated linearly between those values) significantly underestimate the late twentieth century changes in climate relative to simulations in which stratospheric ozone is specified at daily resolution. The differences reach all the way into the troposphere as evident in the magnitude of the poleward shift in near-surface zonal winds and precipitation over the Southern Ocean.

2. Method

In this study we utilize a model that can be configured with and without interactive chemistry to complete three ensembles of simulations of six members each: one ensemble uses fully interactive chemistry to calculate ozone, while the other two ensembles use specified ozone concentrations. We then compare the change in climate, over the second half of the twentieth century, of the two ensembles that used specified ozone concentrations against the change in climate of the ensemble that utilized fully interactive chemistry. We first describe the two configurations of the model and then describe the specifics of each of the three ensembles of simulations.

2.1. Model Configurations

For simulations with interactive chemistry, we utilize the Whole Atmosphere Community Climate Model, a component of the National Center for Atmospheric Research (NCAR) Community Earth System Model, referred to as CESM1(WACCM) or simply WACCM [*Marsh et al*., 2013; *Hurrell et al*., 2013]. WACCM has 66 vertical levels, with the upper boundary at approximately 140 km and a horizontal resolution of 1.9°×2.5°. WACCM includes parameterized gravity waves as well as appropriate treatment of shortwave heating and nonlocal thermodynamic equilibrium radiative transfer in the mesosphere and above. Most importantly, WACCM includes a fully interactive representation of middle atmosphere chemistry that allows for a self-consistent simulation of the stratospheric ozone hole and its effect on tropospheric climate. We also point out that, as configured here, WACCM is the atmosphere component of CESM1 and, for the simulations done in this study, is coupled to an interactive ocean model, land surface model, and sea ice model [*Marsh et al*., 2013; *Hurrell et al*., 2013].

For simulations without interactive chemistry, the "specified chemistry" configuration of WACCM is utilized [*Smith et al*., 2014]. CESM1(SC-WACCM), or simply SC-WACCM, is completely analogous to CESM1(WACCM), including coupling to the ocean, land-surface, and sea ice models, except that nearly all interactive chemistry has been removed. In SC-WACCM, the interactive chemistry of WACCM is essentially replaced by specifying the concentrations of radiatively active constituents, such as CO_2 and ozone, or calculating constituent removal via simple loss mechanisms [*Smith et al*., 2014]. The concentrations or specified values of these species are derived from existing WACCM simulations with interactive chemistry. As in WACCM, the time step of SC-WACCM is 30 min. When the concentrations of radiatively active constituents are specified at coarser temporal resolutions, SC-WACCM determines the value of the constituent at the time step of the model by linearly interpolating between the closest specified values. In time-slice simulations under preindustrial conditions, the simulated tropospheric climate of SC-WACCM, using monthly mean, zonal mean specified constituents, has been found to be indistinguishable from that of WACCM [*Smith et al*., 2014]. This is unsurprising as there are no significant variations in the specified constituents under preindustrial conditions that would be significantly impacted by temporal or spatial smoothing.

2.2. Simulations

The baseline ensemble of simulations consists of six historical integrations of the fully coupled atmosphere-ocean-land configuration of CESM1(WACCM) with interactive middle atmosphere chemistry; these simulations are analogous to those carried out for CMIP5 and are fully described by *Marsh et al*. [2013]. The six members start in 1955, with six different initial conditions, using a method similar to that of *Deser et al*. [2010], and continue until 2005. Concentrations of the ozone-depleting anthropogenic chlorofluorocarbons CFC-11 and CFC-12 are essentially zero before 1960 and increase over the period of this study to 254 parts per trillion by volume (pptv) and 539 pptv, respectively.

To examine the impact of specifying monthly mean ozone values versus specifying ozone at a higher temporal resolution, two SC-WACCM ensembles of six members each were created for comparison to the WACCM ensemble using the same initial conditions as used in the six WACCM simulations. In the first SC-WACCM ensemble, monthly mean, zonal mean stratospheric ozone concentrations were specified, as might be done in a typical CMIP5 model without interactive chemistry, such as NCAR's Community Climate System Model version 4 [*Gent et al*., 2011]. The ozone distribution used on each day is calculated by interpolating between monthly mean values specified at the middle of each month. These simulations will be referred to as SC-WACCM(monthly). In the second SC-WACCM ensemble, the same model setup was used, except that stratospheric ozone was specified as daily mean, zonal mean values. Those simulations will be referred to as SC-WACCM(daily). The specified monthly and daily ozone concentrations are the ensemble mean values from the WACCM (interactive chemistry) ensemble. All other specified constituents in both SC-WACCM ensembles

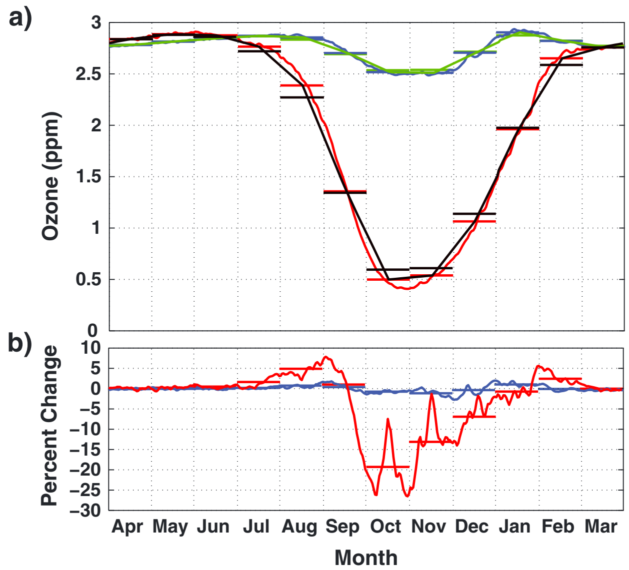

Figure 1. (a) Ensemble mean ozone volume mixing ratio at 52 hPa averaged over the southern polar cap (70–90°S) from 1960 to 1975 in blue and green and from 1990 to 2005 in red and black. The horizontal bars are the monthly mean values, and the curves are the daily mean values. Black and green denote SC-WACCM(monthly), while SC-WACCM (daily) is shown in red and blue. (b) Ensemble mean percent difference in ozone mixing ratio between SC-WACCM(daily) and SC-WACCM(monthly). The curves are the daily mean differences, and the horizontal bars are the monthly mean differences. Red denotes the difference for the 1990–2005 mean, and blue denotes the difference for the 1960–1975 mean.

are the zonal mean, monthly mean values of the WACCM ensemble. Note that all simulations in the SC-WACCM ensembles cover the exact same period as the WACCM ensemble (1955–2005).

2.3. Analysis Details

In Figure 1, we examine the differences in ensemble mean ozone values as simulated by WACCM and specified in the SC-WACCM ensembles. In Figures 2, 3, and 4, the ensemble median was chosen as the best measure of the central tendency of each ensemble due to the significant variability displayed by individual members. In all figures, dots denote the regions of insignificance. In all cases, significance was tested using a Wilcoxon rank sum test of 90 (i.e., 15 years of individual monthly mean values from six ensemble members) monthly values at the 95% level [*Hollander and Wolfe*, 1999].

3. Results

We first compare the monthly mean and daily mean ozone concentrations from the two SC-WACCM simulations to the interactively calculated ozone in WACCM when there is a strong Antarctic ozone hole (1990–2005). We then examine the impact of the biases introduced by specifying monthly mean ozone on certain aspects of SH climate change over the latter half of the twentieth century.

3.1. Effect of Temporal Smoothing on the Antarctic Ozone Hole

Figure 1a depicts the seasonal cycle of ozone at 52 hPa averaged over the southern polar cap (70–90°S), as specified for the SC-WACCM integrations. Two curves show the daily mean ozone in SC-WACCM, averaged over the period 1990 to 2005: red for SC-WACCM(daily) and black for SC-WACCM(monthly). The daily mean ozone in SC-WACCM(daily) is nearly identical to the daily mean ozone of WACCM (not shown since they are indistinguishable), whereas the daily mean ozone of SC-WACCM(monthly) is significantly different. This is directly due to the linear temporal interpolation preformed by SC-WACCM on the specified ozone concentrations. The comparison of the black and red curves in Figure 1a shows that linear interpolation between the specified monthly values does not capture the rapid changes in ozone concentration during the ozone hole season. This causes the concentration of ozone in SC-WACCM(monthly) to be too low at the beginning and end of the ozone hole season and too high during October and November when ozone is at its minimum.

The horizontal bars in Figure 1a show the monthly means of the daily curves: red bars for SC-WACCM(daily) and black bars for SC-WACCM(monthly). It is clear that the process of interpolation used in SC-WACCM(monthly) does not preserve the WACCM monthly mean during the season of rapid changes in ozone (e.g., compare the black and red bars during the ozone hole season).

The percentage differences between the black (monthly) and red (daily) curves in Figure 1a are shown by the red curve Figure 1b together with its monthly means (red bars). During the October ozone minimum, the differences are up to 27%. We note that the large short-term variability in the red curve of Figure 1b, especially in October, November, and December, is an artifact of specifying the ozone at the midpoint of each month and does not represent interannual variability.

In contrast to the late twentieth century, the pre-ozone-hole period is characterized by small month-to-month changes in ozone, and consequently, biases due to interpolation between monthly means are small. This is also

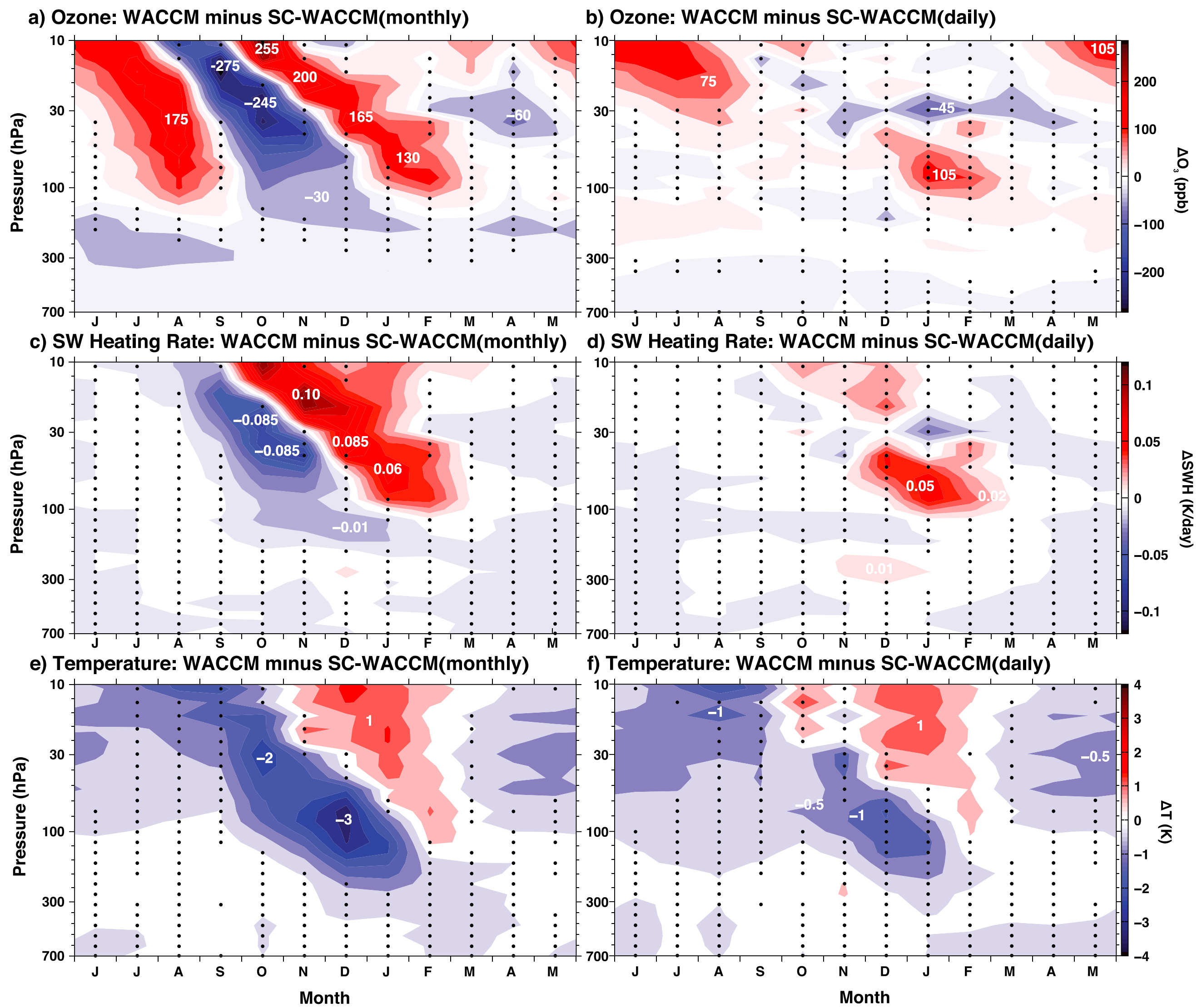

Figure 2. Comparison of the 1990–2005 ensemble median, monthly mean differences between (a, c, and e) WACCM and SC-WACCM(monthly) and WACCM and (b, d, and f) SC-WACCM(daily). Figures 2a and 2b show the southern polar cap (70–90°S) ozone volume mixing ratio differences (ppbv), Figures 2c and 2d show the resulting differences in shortwave heating (K d^{-1}), and Figures 2e and 2f show the subsequent differences in temperature (K). The dotted regions are statistically insignificant at the 95% level as determined by a Wilcoxon rank sum test.

illustrated in Figure 1a, which shows the 1960–1975 daily and monthly mean ozone values from SC-WACCM(monthly) in green and SC-WACCM(daily) in blue. Because the temporal changes in ozone are much smaller in the pre-ozone-hole period, linear interpolation between specified monthly values sufficiently captures the variability of ozone. The percent difference between the pre-ozone-hole period values is quantified in blue in Figure 1b, where the largest differences are no greater than 3%.

We now show that the interpolation biases have a significant effect on stratospheric heating rates and temperatures. Figure 2 displays the ensemble median monthly mean differences in polar cap ozone concentrations, shortwave heating rates, and temperature, as functions of pressure, between the WACCM ensemble and each of the two SC-WACCM ensembles. We first focus on the differences between WACCM and SC-WACCM(monthly) in Figures 2a, 2c, and 2e (Left column of Figure 2). In Figure 2a, the monthly mean ozone volume mixing ratio difference between WACCM and SC-WACCM(monthly) shows a significant tripole pattern between 100 hPa and 10 hPa from June to January (i.e., high in July, low in October, and high again in December, see also the red curve in Figure 1b). At the time of the ozone hole minimum in October, SC-WACCM(monthly) has 245 ppb more ozone than WACCM at 30 hPa.

The resulting differences in shortwave heating are shown in Figure 2c. The tripole pattern seen in Figure 2a gives rise to a dipole pattern in Figure 2c because shortwave heating depends on both the concentration of ozone and incoming solar radiation, which does not occur during the initial overestimate of ozone in austral winter (June-July-August). The temperature differences that follow are shown in Figure 2e. Consistent with the bias in shortwave heating, WACCM is colder than SC-WACCM(monthly) throughout the lower stratosphere. Notably, the temperature bias reaches a maximum of -3 K at 100 hPa in December, which is lower and later than the center of the ozone hole. Figure 2e is directly comparable to Figure 1b of *Waugh et al.* [2009] and validates the result of that study, which shows similar temperature differences between a simulation with interactive ozone chemistry and a simulation with specified monthly mean, zonal mean ozone during the ozone hole period.

Figures 2b, 2d, and 2f compare WACCM to SC-WACCM(daily) (Right column of Figure 2). Figure 2b shows that specifying daily ozone values leads to no significant biases in ozone during the ozone hole period. Thus, the dipole pattern in Figure 2a appears to be primarily attributable to temporal smoothing of specified ozone rather than the use of zonal means. Because of the insignificant differences in ozone, Figure 2d shows only small and spatially incoherent differences in the shortwave heating rates. The resulting differences in monthly mean temperature are seen in Figure 2f. Unlike SC-WACCM(monthly), SC-WACCM(daily) shows only small and mostly insignificant differences in temperature compared to WACCM.

The exceptions to this are during June and July between 50 hPa and 10 hPa when WACCM is ~0.5 K colder and December through February between 30 hPa and 10 hPa when WACCM is ~1 K warmer. These differences are similar to those seen in the same regions of SC-WACCM(monthly), Figure 2e, and are insignificant compared to the bias in the lower stratosphere from October to January in SC-WACCM(monthly). Because these differences are consistent between the two SC-WACCM ensembles, they may be attributable to the effect of spatial smoothing imposed by specifying the zonal mean values.

Figure 2f shows the same result as Figure 3c of *Gillett et al*. [2009], where an interactive chemistry simulation was compared to a simulation with zonal mean ozone specified at every model time step. This suggests that zonal asymmetries must also play a role in the temperature differences between interactive chemistry simulations and specified chemistry simulations. However, the comparison of Figures 2e and 2f suggest that at least half of the monthly mean temperature differences between WACCM and SC-WACCM(monthly) may be attributed to coarse temporal representation of the specified ozone in SC-WACCM(monthly) if we presume that the effects are additive.

3.2. Impacts on Tropospheric Climate

The significant differences in stratospheric temperatures between WACCM and SC-WACCM(monthly) occur during the ozone hole season. As a consequence of these differences, significant differences are found at the end of the twentieth century when comparing the simulated changes in the summertime SH circulation and surface climate between the two ensembles. Differences in the austral summertime (December-January-February (DJF)) temperatures between SC-WACCM(monthly) and WACCM (Figure 2e) are induced by differences in the SH DJF zonal mean winds from the stratosphere down to the surface. To highlight these differences across simulation ensembles, we now focus on decadal average changes in zonal wind for each ensemble.

Figure 3 compares the zonal wind differences between the periods 1960–1975 and 1990–2005, in austral summer (DJF), in WACCM (Figure 3a), SC-WACCM(monthly) (Figure 3b), and SC-WACCM(daily) (Figure 3c). In all three panels, the black contour lines show the ensemble's climatology from 1960 to 1975, and the shading shows the difference between the ensemble medians of 1960–1975 and 1990–2005. Figure 3 is directly comparable to Figure 12 of *Marsh et al*. [2013], and the WACCM ensemble completed for this study is indistinguishable from that of *Marsh et al*. [2013].

The comparison of WACCM to SC-WACCM(monthly) shows that the change in the stratospheric polar vortex over this period is considerably smaller when the monthly mean ozone is specified. In WACCM, the peak difference in the jet at 65°S and 30 hPa is 12.5 m s^{-1}, while in SC-WACCM(monthly), the peak change is only 11.1 m s^{-1}; these differences are statistically significant. Note that in SC-WACCM(daily), Figure 3c, the jet change is nearly identical to WACCM with a peak change of 12.3 m s^{-1}. Thus, the peak changes in zonal winds between the period before and during the ozone hole shown in Figure 3 suggest that temporal smoothing

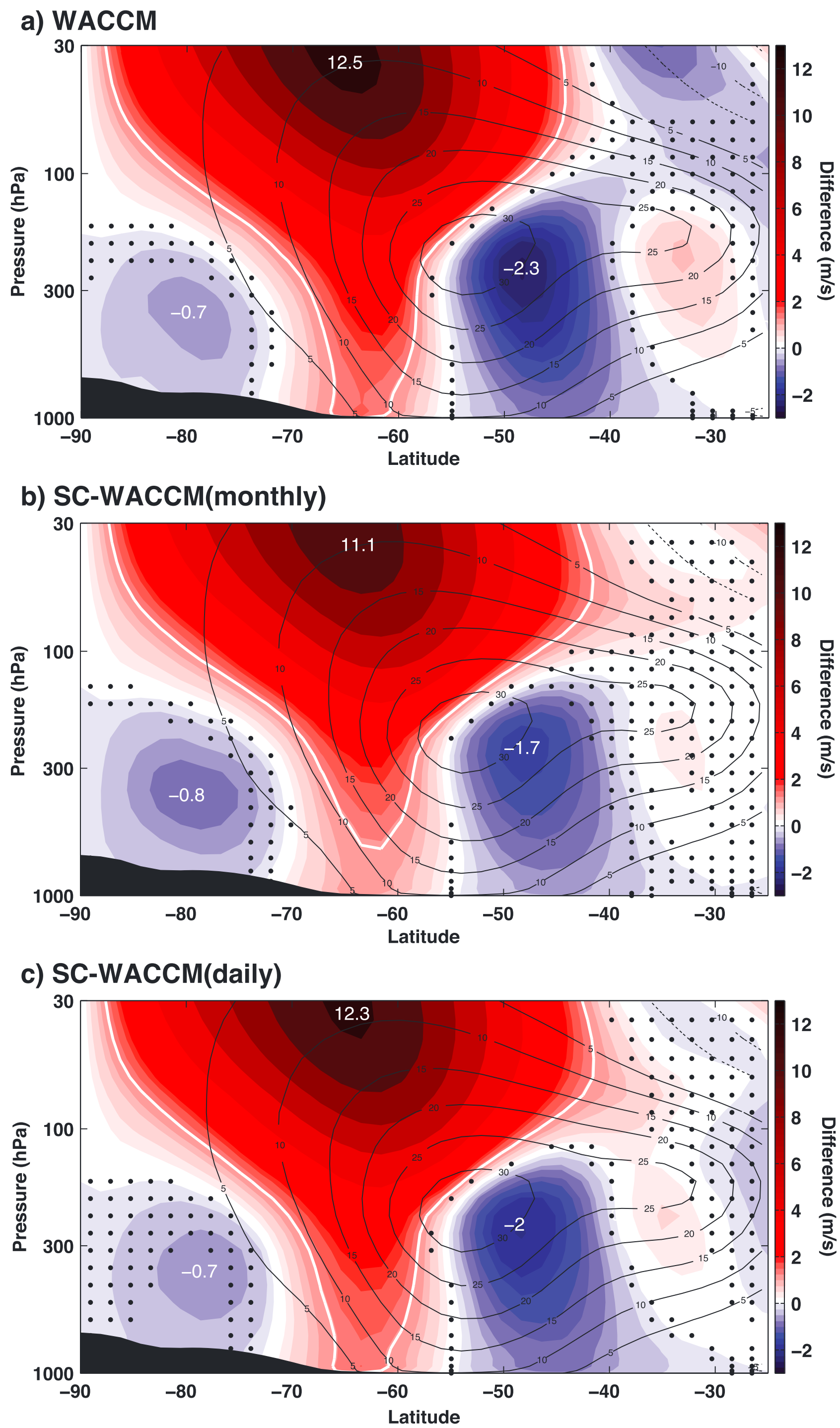

Figure 3. SH DJF ensemble median zonal wind for (a) WACCM and (b) SC-WACCM(monthly) and (c) SC-WACCM(daily). The black contour lines are the 1960–1975 climatology drawn every 5 m/s. The shading shows the difference between the 1990–2005 and 1960–1975 medians of each ensemble. The dotted regions are statistically insignificant at the 95% level. The white contour marks the 1.25 m/s level.

may account for as much as 85% of the difference in stratospheric zonal mean zonal wind between WACCM and SC-WACCM(monthly), assuming that the effects are additive.

Moreover, in the troposphere, all three ensembles show a statistically significant increase of winds on the poleward side of the climatological jet and a decrease on the equatorward side; this pattern is often referred

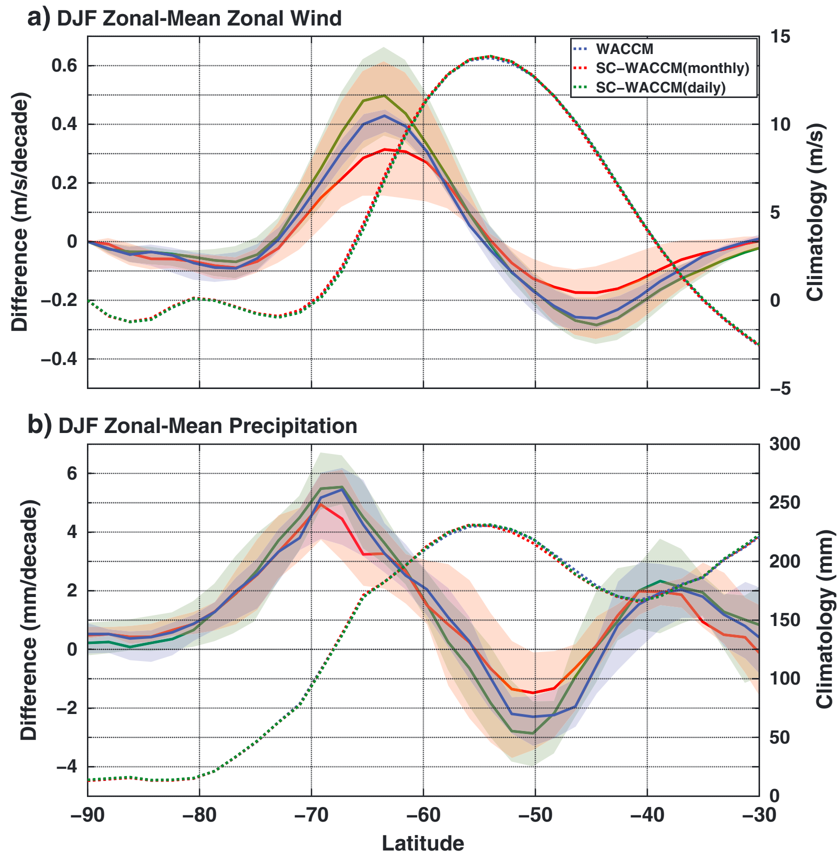

Figure 4. Comparison of the ensemble-median zonal mean differences (solid) and climatologies (dashed) of near-surface winds at 867 hPa and precipitation for WACCM (blue), SC-WACCM(monthly) (red), and SC-WACCM(daily) (green). The differences are taken between the 1990–2005 and 1960–1975 periods, and climatologies represent the 1960–1975 period. The shading represents the range of values between the 10th and 90th percentile across each ensemble's distribution.

as a positive phase of the Southern Annular Mode. The tropospheric wind shifts are highlighted by the white contour, which marks the 1.25 m/s level in each plot. In WACCM and SC-WACCM(daily), this contour clearly reaches the surface, whereas in SC-WACCM(monthly), it does not.

We further examine the bias from using the monthly specified ozone on SH surface climate change by looking at the change in DJF near-surface zonal wind and precipitation between 1960–1975 and 1990–2005 in each of the three ensembles (Figures 4a and 4b, solid lines). For reference, the dashed lines in Figure 4 show the 1960–1975 climatology for each ensemble. The key points of Figure 4 are that SC-WACCM(monthly) (red) only displays approximately three quarters of the peak change in the near-surface zonal wind compared to WACCM (blue) between 75°S and 65°S and approximately half the largest decrease in precipitation near 50°S. In contrast, SC-WACCM(daily) (green) captures a similar change to WACCM. Hence, the specification of monthly mean ozone, which is customary in current generation climate models, has profound consequences on the trends in surface winds and precipitation during the ozone hole period.

4. Discussion and Conclusions

In this study we have examined the dependence of SH climate trends on the frequency at which stratospheric ozone is specified. Specifically, we have examined the impact of using coarse temporal resolution to represent the seasonal cycle in stratospheric ozone. By specifying the monthly mean values and linearly interpolating between these values to the time step of the model, a distinct tripole bias in the ozone concentration is created. The bias is only significant when month-to-month changes in ozone are large, as happens in SH spring during the latter decades of the twentieth century, when the ozone hole develops.

Previous to the development of the Antarctic ozone hole, the impact of using the linearly interpolated monthly mean ozone concentrations is negligible. The bias introduced by linear interpolation is shown to have a significant impact on SH stratospheric temperatures during the ozone hole period and, consequently, on SH climate. Specifically, we show, by comparing WACCM with fully interactive chemistry to SC-WACCM with monthly and daily specified ozone, that specifying the daily mean ozone significantly reduces the differences in SH zonal mean wind and precipitation with respect to WACCM. This result is especially important for upcoming and future CMIP projects, which will need to define how models without interactive middle atmosphere chemistry prescribe the ozone concentrations [*Meehl et al*., 2014].

The results of this study are consistent with previous studies that examine the impact of using specified ozone values in coupled climate model simulations [*Crook et al*., 2008; *Gillett et al*., 2009; *Waugh et al*., 2009]. In particular, the differences in the southern polar cap monthly mean temperature and the changes in the SH zonal-mean winds between fully interactive WACCM and SC-WACCM using linearly interpolated monthly mean ozone are directly comparable in magnitude to the results of *Waugh et al*. [2009], which examined changes over the late twentieth century. In *Waugh et al*. [2009], the differences between simulations with interactive chemistry and those with monthly mean, zonal mean specified ozone values were solely attributed to the impact of specifying a zonal mean via the mechanism described by *Crook et al*. [2008]. Here we show that the impact of specifying ozone at a monthly resolution also accounts for a substantial fraction of those differences.

Similarly in Figure 2, the shortwave heating and temperature differences between WACCM and SC-WACCM(daily) seen in Figures 2d and 2f, respectively, show uniquely the effects of the nonzonality of the ozone concentrations in WACCM. The key point of Figure 2 is that Figures 2b, 2d, and 2f show much smaller differences than those in Figures 2a, 2c, and 2e, indicating that the errors introduced by specifying the zonal mean ozone are relatively small compared to the errors associated with interpolating ozone from monthly mean values.

Here we have shown that by simply increasing the temporal resolution of the specified ozone values from monthly to daily means, a coupled climate model without interactive chemistry captures similar magnitudes of decadal change as those simulated by a fully interactive model.

Although higher temporal resolution is easy to achieve with the use of model output, current observational data sets [e.g., *Cionni et al*., 2011] are limited to monthly mean values. One possible solution would be to employ a method that is frequently used to ensure that the linear time interpolation between specified monthly mean sea surface temperature and sea ice concentrations maintains the correct monthly mean values [*Taylor et al*., 2000]. This method is commonly referred to as "diddling" and simply adjusts the specified monthly mean such that the linear interpolation operator returns the desired monthly mean value. As part of this study, an ensemble of three SC-WACCM simulations was also completed exactly as the SC-WACCM(monthly) except that the monthly mean ozone values were diddled. From this ensemble, we found that diddling, as designed, does reduce the error in monthly mean ozone values compared to WACCM. Yet diddling did not improve the simulated trends in the zonal mean wind or precipitation fields because diddling, by definition, does not reduce the differences between the daily mean ozone values. Other methods such as polynomial interpolation may be needed to more accurately represent temporal variability in ozone, if ozone databases for future model intercomparison projects are to be based primarily on observational information alone.

Acknowledgments
We thank Rolando Garcia, Doug Kinnison, Anne Smith, Francis Vitt, Sean Santos, and Michael Mills for their assistance in developing CESM1 (WACCM and SC-WACCM) and interpreting its output. The CESM project is supported by the U. S. National Science Foundation (NSF) and the Office of Science of the U.S. Department of Energy. The National Center for Atmospheric Research (NCAR) is sponsored by the NSF. The authors also want to acknowledge Robert W. Portman (NOAA/ESRL) for the many fruitful discussions on this topic. The authors acknowledge the NOAA Research and Development High Performance Computing Program for providing computing and storage resources that significantly contributed to the research results reported within this paper (http://rdhpcs.noaa.gov). We also thank Henry LeRoy Miller Jr. (NOAA/ESRL) for his assistance with NOAA's high-performance computing facilities. Computing resources were also provided by the Climate Simulation Laboratory at NCAR's Computational and Information Systems Laboratory, sponsored by the NSF and other agencies. R.R.N. is currently supported by the NSF via the NCAR's Advanced Study Program's postdoctoral fellowship and as a postdoctoral research associate at NOAA/ESRL. K.L.S. is funded by a Natural Sciences and Engineering Research Council of Canada Postdoctoral Fellowship. SMD's participation in this work was funded by NASA ACMAP grant 12-ACMAP12-0010. The work of D.R.M. and L.M.P. is funded, in part, by Frontier of Earth System Dynamics grant (OCE-1338814) from the NSF. All of the original model results produced in this work are freely available via requests to the corresponding author.

The Editor thanks Julia Crook and an anonymous reviewer for their assistance in evaluating this paper.

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