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Key Points:
- WACCM simulations show enhanced chemical ozone loss associated with the 2015 eruption of the Calbuco volcano
- The record ozone hole size in 2015 is mainly attributable to chemical ozone loss associated with the Calbuco eruption
- Comparison of fully coupled and specified dynamic simulations shows that the role of dynamical feedbacks was minimal

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The influence of the Calbuco eruption on the 2015 Antarctic ozone hole in a fully coupled chemistry-climate model

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Abstract Recent research has demonstrated that the concentrations of anthropogenic halocarbons have decreased in response to the worldwide phaseout of ozone depleting substances. Yet in 2015 the Antarctic ozone hole reached a historical record daily average size in October. Model simulations with specified dynamics and temperatures based on a reanalysis suggested that the record size was likely due to the eruption of Calbuco but did not allow for fully coupled dynamical or thermal feedbacks. We present simulations of the impact of the 2015 Calbuco eruption on the stratosphere using the Whole Atmosphere Community Climate Model with interactive dynamics and temperatures. Comparisons of the interactive and specified dynamics simulations indicate that chemical ozone depletion due to volcanic aerosols played a key role in establishing the record-sized ozone hole of October 2015. The analysis of an ensemble of interactive simulations with and without volcanic aerosols suggests that the forced response to the eruption of Calbuco was an increase in the size of the ozone hole by 4.5×10^6 km^2.

1. Introduction

Each austral spring, Antarctic stratospheric ozone undergoes systematic depletion that typically maximizes in late September and October, known as the Antarctic ozone hole [*Farman et al.*, 1985]. In response to concern over ozone depletion, chlorofluorocarbons (CFCs), the primary source of anthropogenic chlorine to the stratosphere, were phased out under the Montreal Protocol. *Solomon et al.* [2016] suggested that in model simulations and observations, healing of the Antarctic ozone hole due to the phase out of CFCs was discernable in the month of September, when the ozone hole is growing in size.

While gas-phase chemistry depletes ozone, it is heterogeneous ozone depletion chemistry occurring upon the surface of polar stratospheric clouds that leads to the severe ozone depletion that creates the Antarctic ozone hole [*Solomon et al.*, 1986]. Volcanic eruptions enhance the amount of aerosols in the stratosphere, effectively increasing the particle surface areas that drive heterogeneous ozone depletion [*McCormick et al.*, 1995; *Deshler et al.*, 1996]. Further, observations show that Antarctic ozone depletion was enhanced after the major eruption of Mount Pinatubo in the early 1990s [e.g., *Portmann et al.*, 1996; *Solomon et al.*, 2005].

Despite the onset of chemical healing of the Antarctic ozone hole, the Antarctic ozone hole reached a record size of 28.2×10^6 km^2 on 2 October 2015 [*Haar and Allen*, 2015; *World Meteorological Organization (WMO)*, 2015]. Cold temperatures and weakened transport were noted among possible drivers in establishing the record size [*WMO*, 2015]. However, *Solomon et al.* [2016] argued that in model simulations with specified dynamics and temperatures from reanalyses, volcanic aerosols due to the eruption of Calbuco in southern Chile (41°S, 72°W) were the dominant contributor to the record in 2015. Because the simulations in *Solomon et al.* [2016] were nudged to reanalyses, these simulations isolated the chemical loss due to enhanced volcanic aerosols but could not be used to quantify the potential effect of dynamical or thermal feedbacks, as any such feedbacks are already incorporated in the reanalyses. Enhanced ozone depletion due to volcanic aerosols could effectively cool the lower stratosphere, and a degree or two of cooling can influence chemical reaction rates [*Rex et al.*, 2004; *Solomon et al.*, 2015]. Whether the spring of 2015 was anomalously

cold due to circulation changes, enhanced ozone depletion associated with enhanced aerosol from the Calbuco eruption, or whether there was a dynamical feedback could not be established from the specified dynamic simulations. Nor did *Solomon et al.* [2016] establish that feedbacks were needed to simulate the 2015 ozone changes.

In this study, we present calculated changes in Antarctic ozone and the size of the ozone hole due to volcanic aerosols from the 2015 eruption of Calbuco in an ensemble of free-running Whole Atmosphere Community Climate Model (WACCM) simulations, which include interactive dynamics and radiation. We compare the differences in key chemical species related to ozone chemistry between simulations with and without volcanic aerosols to the specified dynamics simulations presented in *Solomon et al.* [2016]. We find that in both the interactive and specified dynamics simulations, chemical ozone depletion associated with the eruption of Calbuco increases the ozone hole size by about 4.5×10^6 km^2 in October 2015 and is the leading cause of the record ozone hole in this model.

2. Methods

The response of ozone to enhanced volcanic aerosols was simulated using the National Center for Atmospheric Research's Community Earth System Model, version 1, with its high top atmosphere, the Whole Atmosphere Community Climate Model (CESM1(WACCM) [*Marsh et al.*, 2013]). In this study, we present free-running model simulations (FR-WACCM), with coupled chemistry and dynamics, and compare these to the specified dynamics simulations (SD-WACCM) used in *Solomon et al.* [2016], which are nudged to reanalysis from the Modern Era Retrospective Analysis for Research and Applications (MERRA) *Rienecker et al.*, 2011], available for 1979 through 2014, and from Goddard Earth Observing System operational data for 2015. The SD-WACCM simulations were performed from 1979 to 2015 with historical specified sea surface temperatures, time-varying ozone depleting substances, and time-varying greenhouse gases, as discussed further in *Solomon et al.* [2016]. The SD-WACCM simulations analyzed here include prescribed monthly stratospheric aerosols that were previously calculated with a version of SD-WACCM with a prognostic volcanic aerosol capability based on SO_2 emissions, as discussed in *Mills et al.* [2016]. As in *Solomon et al.* [2016], our calculations prescribe aerosol mass, surface area, and radius as described in *Neely et al.* [2016]. Thus, the aerosols are not transported interactively with model-calculated winds but do vary as they are derived from simulations using reanalyses and time-varying emissions. Furthermore, the aerosols can affect the chemistry and radiation fields. One ensemble of FR-WACCM runs (Vol-Clean) includes only "background" aerosols (from nonvolcanic and continuously outgassing volcanic sources) and a second set of ensemble runs (Volcanic) adds aerosols from explosive volcanic eruptions to the background, based on the updated database of volcanic sulfur dioxide (SO_2) emissions from 1990 to 2015 (see *Mills et al.* [2016] and *Solomon et al.* [2016] for details). All simulations were conducted on NCAR's Yellowstone computing system [*Computational and Information Systems Laboratory*, 2012].

The forcings used in the FR-WACCM simulations are similar to those of the SD-WACCM simulations, with time-varying ozone depleting substances and greenhouse gases, and with the same aerosol forcing files as in SD-WACCM, one including volcanic aerosols and one without. However, the FR-WACCM simulations included an interactive ocean. Since we are interested in 2015 specifically, the FR-WACCM simulations were started in 2011, allowing for a spin-up period and were run through 2015. The simulations were branched from FR-WACCM Volcanic and Vol-Clean simulations run from 2004 to 2011. To provide an estimate of the internal variability, ensembles of eleven simulations were run with each aerosol forcing file, Volcanic and Vol-clean, with slightly perturbed initial conditions for both ensembles. As we seek to estimate the forced response, we present the ensemble mean results.

The daily-mean size of the ozone hole was estimated from total column ozone for both observations and the model simulations. The daily-mean area of the ozone hole was calculated by summing the area of grid cells with daily total column ozone less than 220 Dobson unit (2.69×10^{16} molecules cm^{-2}) over the polar cap (60–90°S). The observations of total column ozone are from the National Aeronautics and Space Administration's Total Ozone Mapping Spectrometer and Ozone Monitoring Instrument (TOMS/OMI, version 8, ozoneaq.gsfc.nasa.gov). TOMS data are available at 1° latitude by 1.25° longitude, and OMI data are available at 1° latitude by 1° longitude, and the merged data are available from 1978 to present.

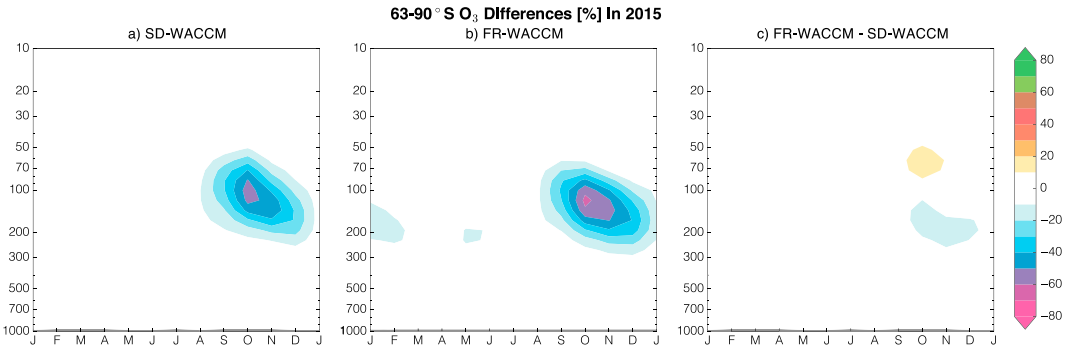

Figure 1. Relative differences in polar cap averaged (63–90°S) ozone between the Volcanic and Vol-Clean WACCM simulations in 2015 for (a) SD-WACCM simulations, (b) FR-WACCM simulation, and (c) the difference between FR-WACCM and SD-WACCM. The month letters indicate the midmonth mean.

3. Results

Figure 1 shows the relative differences in polar cap averaged (63–90°S) ozone between the Volcanic and Vol-clean simulations in 2015 for the ensemble mean FR-WACCM simulations, SD-WACCM simulations, and the difference between the FR-WACCM and SD-WACCM simulations. The model simulations with volcanic aerosols show lower ozone abundances with peak ozone reductions of 50–60% in October at 100–200 hPa, compared to the simulations without volcanic aerosols. We note that the ozone losses associated with volcanic aerosols peak at a lower altitude than the historical (1970–2000) peak altitude of ozone depletion (around 70 hPa), which is consistent with earlier studies [*Solomon et al.*, 2005]. Overall the FR-WACCM and SD-WACCM simulations reveal remarkably similar ozone losses in response to volcanic aerosols. The FR-WACCM simulations show a slightly larger response by about 10–20% in the lowermost stratosphere (150–200 hPa) in October through December and a slight increase by about 10–20% in ozone at 60 hPa in October and November, but overall, the responses between the fully coupled and specified dynamics simulations display close agreement.

While the ozone losses in 2015 are of similar magnitude between the two simulations, some of the ozone loss in the FR-WACCM runs may be attributable to changes in transport or temperatures, as well as chemical depletion. Therefore, we also examined the differences between the Volcanic and Vol-clean CESM1(WACCM) simulations for several keys species relevant to ozone chemistry (Figure 2). Volcanic aerosols effectively provide greater particle surface area to drive heterogeneous chemistry. HCl and $ClONO_2$ react on particles to form active chlorine (Cl_2 and HOCl), and this reaction occurs in the absence of sunlight [*Solomon et al.*, 2015]. The simulations with volcanic aerosols show a decrease in HCl and an increase in ClO_x (defined as the inorganic chlorine that is not included in $ClONO_2$ or HCl), reflecting an increase in the activation of chlorine from the reservoir species. In contrast, late in the ozone hole season, there is an increase in HCl in October in the simulations with volcanic aerosols. As ozone abundances become extremely low, the formation of ClO ceases due to the lack of ozone. As production of Cl exceeds loss, the active chlorine is rapidly converted to HCl. Thus, in the simulations with volcanic aerosols, in which ozone abundances are reduced, more of the active chlorine is converted to HCl, resulting in higher HCl abundances in October for the simulations with volcanic aerosols (Figure 3). $ClONO_2$ is correspondingly reduced in the simulations with volcanic aerosols as more HCl is formed, as less NO_2 is formed due to the lack of ozone reacting with NO. Furthermore, the results shown in Figure 3 including volcanic aerosol are broadly consistent with observations for vertically resolved ozone and HCl from Aura Microwave Limb Sounder (MLS). However, compared to MLS, both WACCM simulations generally underestimate the amount of HCl in 2015, which could affect the simulated ozone sensitivity to the volcanic aerosols.

While the relative differences in O_3, HCl, $ClONO_2$, and ClO_x between the Volcanic and Vol-clean simulations are similar in FR-WACCM and SD-WACCM, we find that the absolute abundances of ozone in winter are higher in the FR-WACCM simulations (Figure 3). Similarly, polar cap averaged (63–90°S) total column ozone in August is also higher by 5% in the FR-WACCM simulations than in SD-WACCM (not shown), leading to an underestimation in the model-calculated size of ozone hole.

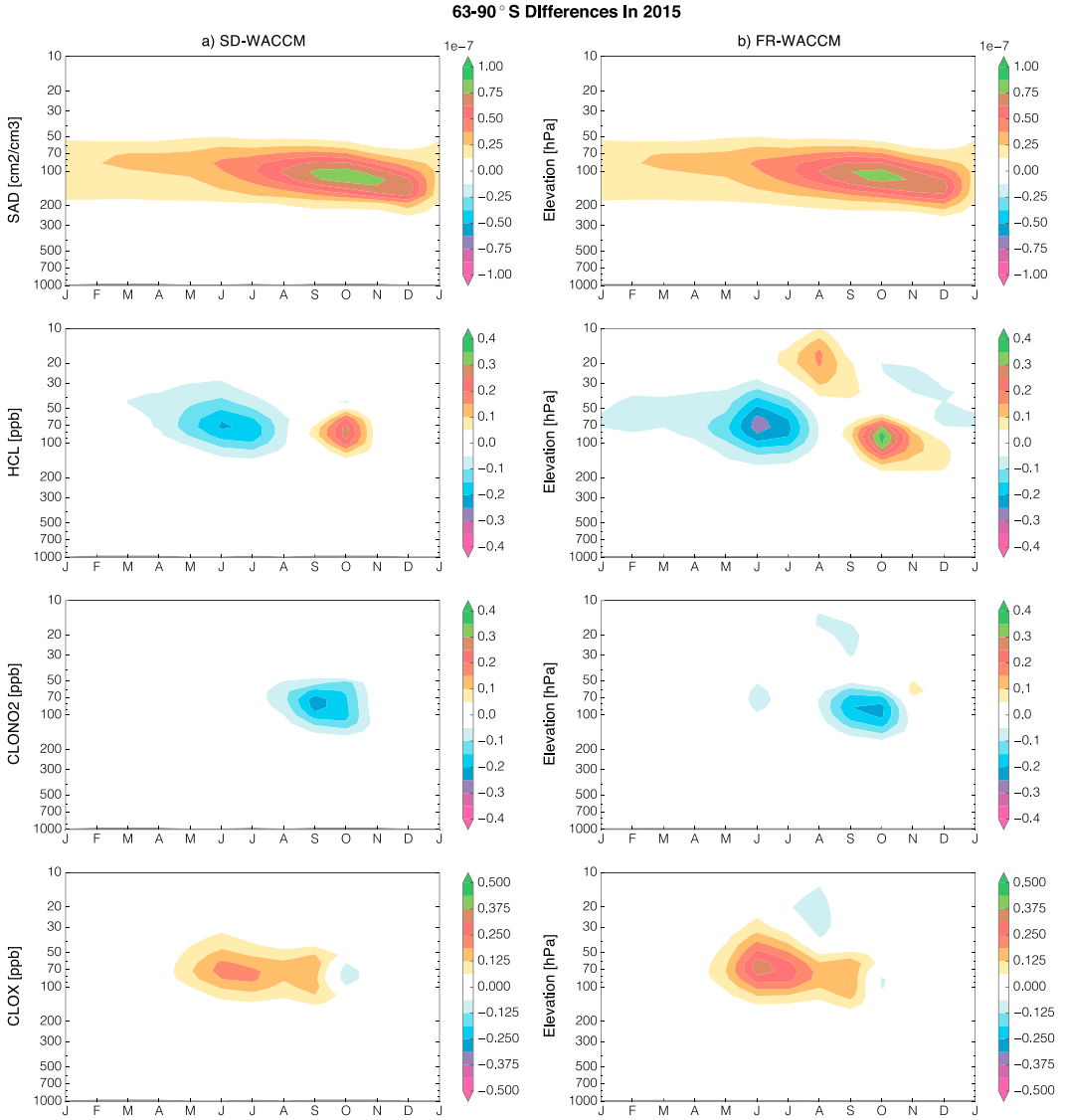

Figure 2. Differences in polar cap averaged (63–90°S) sulfate aerosol surface area density (SAD), HCl, $ClONO_2$, and ClO_x in 2015 between the Volcanic and Vol-Clean simulations in (a) SD-WACCM and (b) FR-WACCM. The month letters indicate the midmonth mean.

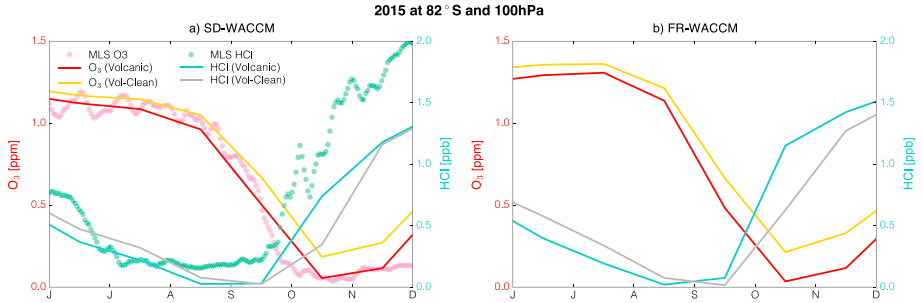

Figure 3. Monthly mean O_3 and HCl at 82°S and 100 hPa from the Volcanic and Vol-Clean simulations for (a) SD-WACCM and (b) FR-WACCM. Observations from MLS are also shown with SD-WACCM. The month letters indicate the beginning of the month.

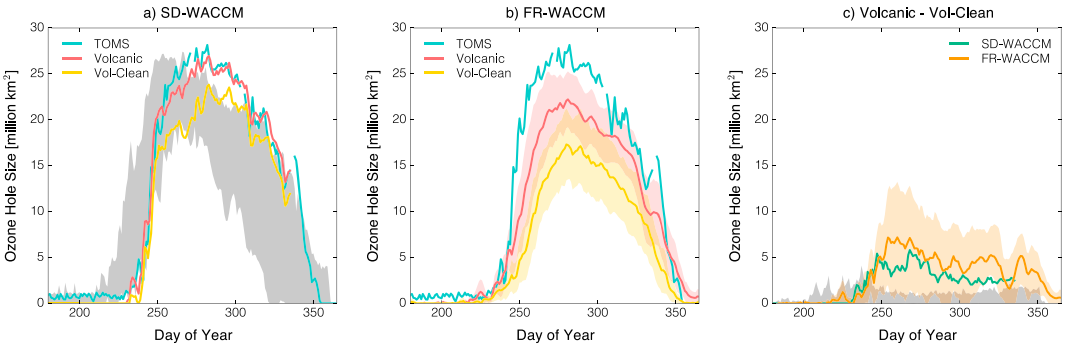

Figure 4. Size of the Antarctic ozone hole by day of year calculated from total column ozone for (a) observations (TOMS) and SD-WACCM and (b) FR-WACCM simulations. The grey shading shows the range of the ozone hole size based on observations (TOMS) for 2000 to 2014 and the lines show the ozone hole size in 2015 from (blue) TOMS/OMI and the (pink) Volcanic and (yellow) Vol-Clean simulations. The pink and yellow shading on the FR-WACCM results show the 95% confidence intervals, based on a two-sided Student's *t* test. (c) Differences in the size of the Antarctic ozone hole size between the Volcanic and Vol-Clean WACCM simulations. The grey shading shows the range of differences from 2000 to 2014 from SD-WACCM, the lines show the differences in the size in 2015 simulated by (green) SD-WACCM and (orange) FR-WACCM, and the orange shading shows the 95% confidence interval, based on a two-sided Student's *t* test, for the differences in sizes simulated with FR-WACCM .

Figures 4a and 4b show the size of the Antarctic ozone hole by day of year over the last 15 years (2000–2015) calculated from total column ozone observations from TOMS/OMI and 2015 for SD-WACCM and FR-WACCM model simulations. As seen in the observations from TOMS, the ozone hole in 2015 lasted longer than in previous years (2000–2014, grey shading), establishing it as a "record year." Overall, SD-WACCM simulates the size of the Antarctic ozone hole fairly well (as also seen in *Solomon et al*. [2016]). The Volcanic SD-WACCM simulation time series of ozone hole size is nearly identical to that estimated from observations. However, when the 2015 Calbuco eruption (Vol-Clean SD-WACCM simulation) is not included, the simulation produces an ozone hole size in 2015 that is 12.6% smaller than that observed/simulated when including the eruption. FR-WACCM also shows a larger ozone hole in the simulations with volcanic aerosols. However, the absolute magnitude of the ozone hole size in FR-WACCM is smaller than the SD-WACCM simulations and observations likely due to the high ozone bias in the preceding winter. The difference for volcanic versus nonvolcanic conditions is, however, insensitive to these model differences. Figure 4c shows the differences in the daily size of the Antarctic ozone hole between volcanic and volcanically clean calculations from FR-WACCM and SD-WACCM in 2015. Overall, the SD-WACCM and FR-WACCM simulations give similar responses to the inclusion of volcanic aerosols, with the differences in size starting around day 240 and peaking between and after days 250–270. Furthermore, the shading in Figure 4 shows the differences in the ozone hole size from volcanic eruptions for 2000–2014 from the SD-WACCM simulations, suggesting that the influence of Calbuco was unprecedented in the past 15 years. Interestingly, in earlier years the SD-WACCM simulations display an earlier response to volcanic aerosols than in 2015. This is likely due at least in part to the Antarctic ozone hole forming later due to reduced available chlorine [*Solomon et al*., 2016].

4. Conclusions

Simulations using CESM1(WACCM) with interactive dynamics (FR-WACCM) and specified dynamics (SD-WACCM) show that the record Antarctic ozone hole size of 2015 was enhanced due to volcanic aerosol associated with the eruption of Calbuco. The SD-WACCM simulations, while constrained to the observed dynamics and temperatures, produce an Antarctic ozone hole size that is similar to observations (Figure 4) and suggest that the record is attributable to enhanced chemical ozone depletion due to enhanced volcanic aerosols. However, by design the SD-WACCM simulations do not allow quantification of the potential role of temperature or dynamical feedbacks. Here we have shown that an ensemble of FR-WACCM simulations gives similar-magnitude ozone losses and increase in ozone hole size on average of similar magnitude to the effects of volcanic aerosols in SD-WACCM simulations. Comparison of key species related to ozone chemistry between the two models setups suggests that indeed chemical ozone depletion was the primary driver of the record ozone hole size in 2015 and that dynamical/temperature feedbacks were less important.

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