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Significant Contributions of Volcanic Aerosols to Decadal Changes in the Stratospheric Circulation

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Key Points:
- We demonstrate that the volcanic aerosol effect is the primary signal dominating the pattern of decadal variability in the BD circulation
- Main difference between observations and climate models concerns changes in the depth and strength of the aerosol effect on BD circulation
- We demonstrate that Northern Hemisphere slowdown is partly driven by minor volcanic eruptions after 2008

Supporting Information:
- Supporting Information S1

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Abstract The stratospheric circulation is an important element of climate as it determines the concentration of radiatively active species like water vapor and aerosol above the tropopause. Climate models predict that increasing greenhouse gas levels speed up the stratospheric circulation. However, these results have been challenged by observational estimates of the circulation strength, constituting an uncertainty in current climate simulations. Here, we quantify the effect of volcanic aerosol on the stratospheric circulation focusing on the Mount Pinatubo eruption and discussing further the minor extratropical volcanic eruptions after 2008. We show that the observed pattern of decadal circulation change over the past decades is substantially driven by volcanic aerosol injections. Thus, climate model simulations need to realistically take into account the effect of volcanic eruptions, including the minor eruptions after 2008, for a reliable reproduction of observed stratospheric circulation changes.

Plain Language Summary The upper atmospheric circulation is an important element in the climate system as it determines the distributions and lifetimes of key greenhouse gases and impacts the Earth's radiation budget and surface climate. Current climate models rather uniformly predict that increasing greenhouse gas levels speed up the upper atmospheric circulation. However, these results contrast with observations, constituting a major uncertainty in current climate simulations. Our paper shows that the observed pattern of decadal circulation change over the past few decades is substantially driven by volcanic aerosol injections. The recently observed slowdown of the stratospheric circulation in the Northern Hemisphere is by 50% attributable to stratospheric aerosol from minor volcanic eruptions after 2008, which should no longer be neglected in climate simulations.

1. Introduction

The stratospheric circulation, known as the Brewer-Dobson circulation (Bönisch et al., 2011; Butchart, 2014), is an important element of climate as it determines the lifetime and concentration of key greenhouse gases, such as H_2O, CH_4, and O_3, as well as the amount of stratospheric water vapor (Riese et al., 2012; Solomon et al., 2010) and aerosol above the tropopause (Solomon et al., 2011). Climate models predict that increasing greenhouse gas levels speed-up the stratospheric circulation (e.g., Butchart et al., 2010; Garny et al., 2011).

However, these climate model results have been challenged by observational estimates of the circulation strength (Engel et al., 2009; Haenel et al., 2015; Mahieu et al., 2014; Ray et al., 2014), constituting an uncertainty in current climate simulations. Recent model simulations (Diallo et al., 2012; Ploeger, Riese, et al., 2015) driven by meteorological reanalysis (e.g., Dee et al., 2011; Kobayashi et al., 2015) suggest that the pattern of stratospheric circulation change is more complicated than a uniform speedup. The stratospheric circulation changes over the last decades derived from in situ and satellite measurements of trace gases (Engel et al., 2009; Stiller et al., 2012) are consistent with these model simulations. This consistency indicates an important role of natural variability (e.g., quasi-biennial oscillation (QBO), El Niño–Southern Oscillation (ENSO), and volcanic eruptions) for decadal circulation change. The natural variability is strongly constrained by assimilation in the meteorological reanalysis data but difficult to represent reliably in climate models.

Volcanic aerosols from major eruptions (e.g., Pinatubo in June 1991) are well known to have a significant effect on global climate, particularly on stratospheric ozone and temperature (Hansen et al., 1996; Tilmes et al., 2011). The stratospheric aerosol originates from injected carbonyl sulfide (OCS) and sulfur dioxide (SO_2) oxidized to sulfuric acid (H_2SO_4), which then condensates to form a layer of fine sulfate aerosol droplets (H_2SO_4/H_2O) also known as the *Junge Layer* (Junge & Manson, 1961). In particular, during the major eruption of Mount Pinatubo, large amounts of aerosol were directly injected into the tropical lower and mid stratosphere (e.g., Vernier et al., 2011). Stratospheric aerosol particles induce cooling at the surface by reflecting some of the incoming solar energy back to space and heating in the stratosphere by absorbing some of the solar radiation and near-infrared radiation emitted by the Earth's surface. Recently, the volcanic aerosol injection into the extratropical lowermost stratosphere from the post-2008 minor volcanic eruptions (in contrast to Pinatubo) was found to significantly contribute to the stratospheric volcanic aerosol optical depth (AOD) (Andersson et al., 2015; Fromm et al., 2014; Vernier et al., 2011). Even the aerosol contribution from a series of minor volcanic eruptions during the first decade of the twenty-first century has been shown to have the potential to cause significant surface cooling (Solomon et al., 2011) and likely contributed to the recent decadal fluctuations in global warming (Huber & Knutti, 2014; Santer et al., 2014; Schmidt et al., 2014).

Here we attempt to quantify the impact of volcanic eruptions on changes in the pattern of the stratospheric circulation over the past few decades. We particularly focus on the Pinatubo eruption, which shows the clearest and most persistent signal in the lower stratosphere (see Table S1 in the supporting information). We describe the observational data record, the mean age, and multilinear regressions in section 2. Section 3 contains evidence for the impact of volcanic eruptions on stratospheric mean age and its trends. Finally, we discuss our results in the context of the puzzling discrepancy between climate models and observations regarding a potential acceleration of the stratospheric BD circulation.

2. Method and Data

2.1. Models

The results presented here are based on calculated mean age of stratospheric air (see section 2.2 for a definition) and observational stratospheric AOD from satellites. We used mean age calculated with CLaMS (Ploeger, Riese, et al., 2015) and TRACZILLA (Diallo et al., 2012) models, both driven by meteorological reanalysis data. Both simulations used 3-hourly horizontal winds and diabatic heating rates, as the vertical velocity in isentropic coordinates, both from ERA-Interim (ERA-I) (Dee et al., 2011) and Japanese 55 year Reanalysis (JRA-55) (Kobayashi et al., 2015) provided by the European Centre for Medium-Range Weather Forecasts and the Japan Meteorological Agency.

2.2. Mean Age of Air

Mean age in the CLaMS model is calculated from a "clock tracer" that is an inert tracer with a linear increase in the lowest model layer at the surface (Hall & Plumb, 1994). Further details about the CLaMS model and the specific simulation are described by Ploeger, Riese, et al. (2015) and Pommrich et al. (2014). For comparison, we consider mean age calculations from the Lagrangian trajectory model, TRACZILLA (Legras et al., 2005), using the setup described by Diallo et al. (2012, 2017) . Both CLaMS and TRACZILLA mean age simulations have been thoroughly validated with balloon-borne measurements and Michelson Interferometer for Passive Atmospheric Sounding (MIPAS) satellite observations of CO_2 and SF_6, giving confidence in their robustness (Diallo et al., 2012; Ploeger, Riese, et al., 2015). Even regarding decadal variations in the mean age, there is agreement between the simulations and observations, both for the hemispheric asymmetry in the pattern of the circulation change during the last decade (2002–2011) and for the long-term weak increase of mean age in the Northern Hemisphere upper stratosphere (Diallo et al., 2012; Ploeger, Riese, et al., 2015).

2.3. Stratospheric Aerosol Optical Depth

Global stratospheric AOD is estimated from the monthly mean extinction ratio profile, which is the ratio between the particulate and molecular extinction, and is a proxy for the aerosol mixing ratio. Here we use AOD based on SAGE II (Stratospheric Aerosol and Gas Experiment) (1985–2005), on GOMOS (Global Ozone Monitoring by Occultation of Stars) (September 2005 to May 2006) , and on CALIPSO (CloudSat and the Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation) (June 2006 to December 2012)

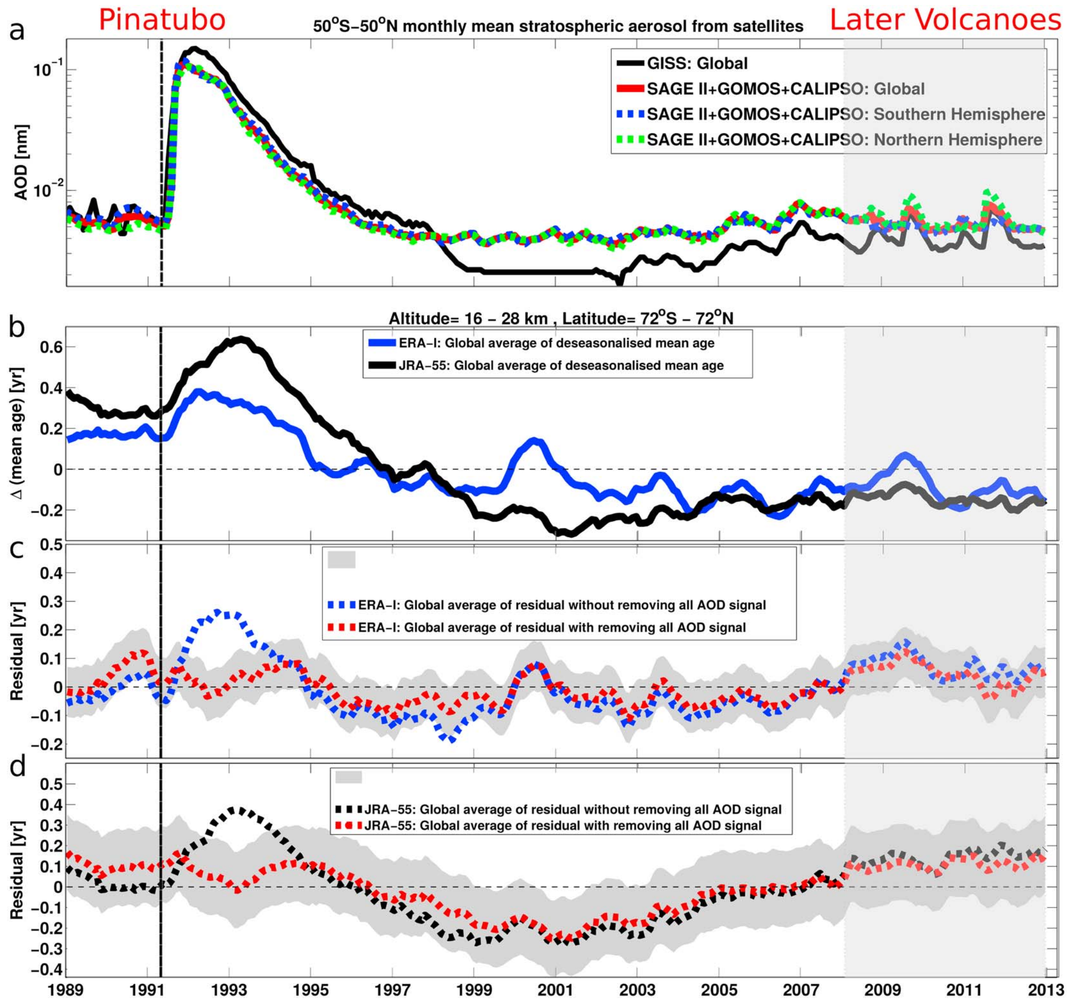

Figure 1. Globally averaged time series of the stratospheric AOD, deseasonalized mean age, and residual of the multiple linear regression with and without removal of all AOD signal. (a) Stratospheric AOD time series is averaged from 50°S to 50°N over the 1989–2012 time period and is shown for merged satellites data sets (GISS: black and SAGE II+GOMOS(525 nm)+CALIPSO (532 nm): red, blue, and green). (b) The deseasonalized mean age driven by ERA-I and JRA-55 reanalyses is globally averaged between 72°S and 72°N and 16–28 km. (c and d) The residual of the multiple linear regression with (red dashed line) and without (black dashed line) removing the AOD signal from the deseasonalized mean age (Figure 1b). The gray shading area indicates the standard deviation.

measurements (red line in Figure 1a). In order to gain confidence in the robustness of our results, we have also used other global stratospheric AOD data sets from the Goddard Institute for Space Studies (GISS) (Sato et al., 1993) and SAGE II merged with OSIRIS (Optical Spectrograph and Infrared Imaging System) (Bourassa et al., 2012).

Figure 1a shows the global stratospheric AOD from different merged satellite observations (Sato et al., 1993; Vernier et al., 2011). Most noticeable is the strong peak in aerosol loading between June 1991 and December 1997 associated with the Pinatubo eruption. The Pinatubo plume instantaneously reached the stratosphere because of its high intensity and tropical location and was further uplifted by enhanced tropical upwelling during the easterly phase of the quasi-biennial oscillation (QBO) (Trepte & Hitchman, 1992). The long lasting aerosol enhancement related to the Pinatubo eruption masked the impact of other weaker eruptions with stratospheric influence occurring during this period, including Cerro Hudson in October 1991 and Rabaul in Papua New Guinea in September 1994. The 1998–2002 period shows no discernible volcanic enhancement in the stratosphere and will be referred to as “quiescent period” in the following. There is only a small and slow rise in stratospheric AOD from 2002 to 2005 followed by two tropical volcanic eruptions (Soufrière Hills on 20 May 2006 and Tavurvur on 7 October 2006) that lead to the peak in AOD time series in 2007. After 2008, there is a small but significant aerosol enhancement (Solomon et al., 2011) in the extratropical lowermost stratosphere due to a series of volcanic eruptions, such as Chaitén, Okmok, Kasatochi, Sarychev, Merapi, Grímsvötn, Nabro, and Puyehue-Cordón Calle (Bourassa et al., 2010; Carn et al., 2016; Haywood et al., 2010) (see Table S1). In contrast to Pinatubo, the aerosol that originated from these later volcanic eruptions rose slowly in the tropics and was mainly transported into the extratropical Northern Hemispheric stratosphere up to an altitude of about 25 km within 1 year. These post-2008 eruptions persistently enhanced the Junge layer in the extratropical lowermost stratosphere (Andersson et al., 2015; Vernier et al., 2011).

3. Effect of Volcanoes on Mean Age and Its Trend

A common metric of the stratospheric circulation is the mean age of stratospheric air (Waugh & Hall, 2002), which is defined as the mean residence time of an air parcel in the stratosphere since its entry across the tropopause. The pattern of mean age trends reveals the pattern of changes of the stratospheric circulation. Our primary focus is on the impact of all volcanic eruptions on the pattern changes of the stratospheric circulation over the past few decades (Haenel et al., 2015) with a particular focus on the Pinatubo eruption, which shows the clearest and most persistent signal in lower stratospheric temperatures (Andersson et al., 2015). Figure 1b shows a clear imprint of the volcanic signal on the deseasonalized mean age during the Pinatubo period. The signal of increasing mean age after the Pinatubo eruption is consistent for simulations driven by both ERA-I and JRA-55 reanalyses.

We quantify the effect of the volcanic aerosol from all volcanic eruptions on mean age and its trends using a multiple linear regression model for the 1989–2012 period. Signals of natural variability such as QBO and El Niño–Southern Oscillation (ENSO) are known to influence the stratospheric circulation and mean age of air (Baldwin et al., 2001; Randel et al., 2009). Therefore, this regression method decomposes the temporal evolution of the monthly zonal mean age in terms of a linear trend, seasonal cycle, QBO, El Niño Southern–Oscillation (ENSO), AOD, and a residual (for details see equation (S1) in section S1 in the supporting information, or Diallo et al., 2012). We disentangle the contribution of the volcanic signal to the mean age calculated from simulations with the Chemical Lagrangian Model of the Stratosphere (CLaMS). CLaMS simulations are driven by ERA-Interim (Dee et al., 2011) and JRA-55 (Kobayashi et al., 2015) meteorological reanalysis fields. In particular, the ERA-Interim-driven CLaMS simulation has been shown to yield mean age largely consistent with spaceborne observations (Ploeger, Riese, et al., 2015). The regression of the mean age is performed both with and without including the term representing the volcanic aerosol signal in the multiple linear regression to isolate the impact of the volcanic aerosol on the mean age and its trend. For representing the mean age variations related to volcanic aerosols, the global AOD time series from merged satellites measurements (Vernier et al., 2011) were used in the multiple linear regression model.

Figures 1c and 1d depicts the residual from the regression (ϵ in equation (S1) in the supporting information) with and without the removal of the AOD signal related to all volcanic eruptions from the mean age. Without removing the AOD signal (blue and black dashed lines), the variability in the residual closely follows the variability in the deseasonalized mean age (Figure 1b). Removing the AOD signal by including the term of volcanic signal in the linear regression significantly reduces the variability in the residual particularly after the Pinatubo eruption (red dashed line in Figures 1c and 1d). Remarkably, including the volcanic aerosol signal in the multiple linear regression substantially reduces the globally averaged mean age linear trend from −0.16 year/decade (without including the AOD signal) to −0.12 year/decade, that is, by about 25% with a p value of 0.2. This demonstrates the robustness of the regression method and corroborates the correlation between the variability in mean age and volcanic aerosols. There is also a reduction in the residual during the volcanically quiescent 1997–2000 period, which is perhaps due to existing correlation between the volcanic eruptions and the strongest ENSO event (1997/2000) (Adams et al., 2003). The reduction of the variability in the residual for the later period after 2008 appears small and is partly canceled due to the global average and the asymmetry of later volcanic eruptions with Northern Hemispheric predominance. Therefore, averaging the effect of the later volcanoes in the Northern Hemisphere shows a significant increase in mean age and reduction of the variability in the residual during the volcanically active period after 2008 (Figure S1).

Figure 2a shows the impact of volcanic aerosol on the stratospheric circulation as estimated from mean age. The mean age changes induced by volcanic aerosol from all volcanic eruptions (1989–2012) are quantified from the term b_3 in equation (S1) normalized by the standard deviation (STD) of the AOD. The dominant signal in the whole AOD time series is associated with the Pinatubo eruption. The figure shows evidence

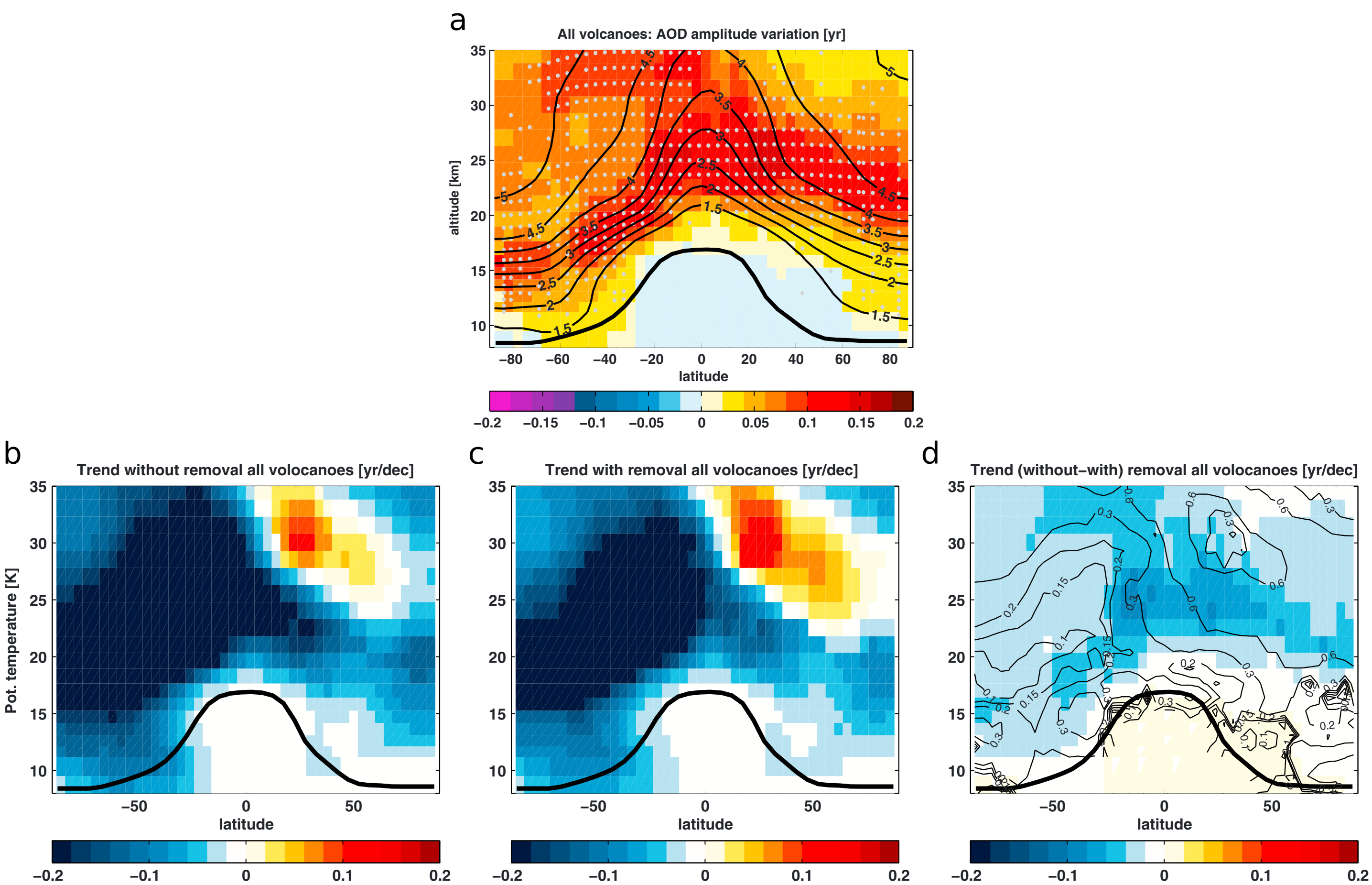

Figure 2. Zonal mean distribution of (a) volcanic aerosol effect on mean age and (b–d) its decadal trends. The amplitude of the mean age variations (term $b_3 \times$ STD(aod)) attributed to the volcanic aerosol from all eruptions since Pinatubo eruption are calculated by using AOD signal from the 1989–2012 period. Bold black line indicates the tropopause height. Black contours show the averaged mean age of air in the 1992–1994 period after Pinatubo eruption. Gray dots indicate statistical significance at 95% level estimated from the Student's *t* test for the all volcanoes. The decadal mean age changes are calculated as a linear trend (term *a*) from the multiple linear regression without including the AOD signal (Figure 2b) and with including the AOD signal (Figure 2c). The difference between the two quantities (without-with) is by definition the volcanic effect on the mean age trends (Figure 2d). This difference is directly comparable to the volcanic effect in Figure 2a, if multiplied with −1, as the Pinatubo eruption occurs at the beginning of the considered period. Figure 2d contours show the fractional change of the trend between Figure 2c–2b.

for an increase of mean age by up to 0.25 year throughout the lower and midstratosphere following the eruption (Figure 2a). The results shown here are based on CLaMS and are analogously reproduced for TRACZILLA simulations in the supporting information (Figure S2). This increase of the mean age did not occur instantaneously but evolved in time as shown in Figure S3. During the first 6 months after the Pinatubo eruption, mean age mainly increased in the extratropical stratosphere above 22 km, while it decreased below that level and also in the deep tropics. The decrease of the mean age indicates increasing upwelling in the deep tropics directly after the eruption, which is consistent with the response in climate models (Garcia et al., 2011). However, after a few months, the increase in mean age spreads into the tropical stratosphere until spring 1993 when the maximum effect of Pinatubo on mean age is observed (Figures 1b and S3). This maximum impact of Pinatubo on mean age arises within the latitude band of approximately 20°S to 30°N and between 20 and 27 km where aircraft and satellite observations of the volcanic plume show a steep meridional gradient of aerosol (McCormick et al., 1995). These results are also consistent with the mean age changes calculated by subtracting the quiescent period (1998–2000) from the Pinatubo period (1992–1994) (Figure S4a). The difference between the standard deviation of the residual (ϵ in equation (S1) in the supporting information) with and without removal of the AOD signal shows a significant variability in the residual if the volcanic effect is not taken into account in the multiple linear regression (Figure S4b). This changing pattern in the residual is similar to the explicitly calculated volcanic effect for the Pinatubo period (Figure 2a). Therefore, a significant variability remaining in mean age after removing the seasonal cycle, QBO, and ENSO signals can indeed be attributed to stratospheric volcanic aerosol.

The statistical significance of the volcanic aerosol effect on the mean age has been assessed by performing a Student's *t* test. For more detail about the statistical analysis see Diallo et al. (2012) and the supporting information. The gray dots in Figure 2a show the one-sided *p* value of the Student's *t* test for the hypothesis of a null volcanic effect on the mean age. The whole region of a large volcanic effect on the mean age is highly significant. This indicates that the volcanic aerosol effect on mean age in the lower and midstratosphere in Figure 2, which is mainly dominated by the Pinatubo eruption, is statistically robust.

Figures 2b–2d shows the stratospheric circulation changes, measured in terms of mean age trends (linear term *a* in equation (S1) in the supporting information), for the 1989–2012 period, without (Figure 2b) and with (Figure 2c) removing the volcanic aerosol signal in the multiple linear regression. Note that a negative mean age trend corresponds to a speedup of the stratospheric circulation and a positive mean age trend to a slowdown. For the 1989–2012 period, the calculation without including the AOD term in the multiple linear regression (Figure 2b) leads to a more strongly negative trend of the mean age in the Southern and Northern Hemisphere lower stratosphere below 24 km and to a weakened positive trend in the Northern Hemisphere above 24 km than including the AOD term (Figure 2c). The difference between mean age trends with and without removing the AOD signal demonstrates the aging effect of the volcanic aerosol on the mean age (Figure 2d). The trend is more negative if the effect of volcanic eruptions is not removed from the mean age decadal variability. Evidently Pinatubo eruption has a strong impact on mean age trends in the lower and mid stratosphere in the 1989–2012 period, changing the magnitude of the mean age trends by up to 0.2 year/decade (e.g., up to 60%) throughout that region.

An important remaining question concerns the dynamical mechanism involved in the stratospheric circulation changes related to volcanic aerosol injections. The clearest picture can be expected to emerge for the major eruption of Pinatubo on which we concentrate our discussion in the following. An estimate of the response of the tropical upwelling velocity $\overline{w}^*$ to volcanic aerosol injections can be deduced from the latitudinal gradient of mean age of air (e.g., SPARC CCMVal report, chapter 5, Eyring et al., 2010; Strahan et al., 2011). Following the arguments of Neu and Plumb (1999), the extratropics-tropics mean age difference is directly related to the (inverse) upwelling velocity, $\Delta\Gamma \sim 1/\overline{w}^*$, and independent of the mixing strength (see Linz et al., 2016 for a more recent discussion). Figure 3 shows the latitudinal gradient of the net volcanic effect on mean age and its trends (Figure 3a) as well as the $\overline{w}^*$ estimate (Figure 3b). The distinct pattern with a negative effect on the mean age gradient above about 22 km and a positive effect below indicates increasing tropical upwelling above 22 km related to volcanic aerosol (noting $\Delta\Gamma \sim 1/\overline{w}^*$) and decreasing upwelling below. This result agrees well with the $\overline{w}^*$ estimate, which shows an increasing tropical upwelling at the upper levels and decreasing upwelling at the lower levels related to volcanic aerosol (Figure 3b), i.e., a strengthening of the BD circulation (advective) above 22 km and its weakening below. The latitudinal gradient estimated from the net volcanic effect on the mean age trend is positive above 22 km (Figure 3a). This implies a negative volcanic effect on the trend of the tropical ascent rate (noting $d(\Delta\Gamma)/\mathrm{d}t \sim -\mathrm{d}\overline{w}^*/\mathrm{d}t$).

The clear increase of tropical upwelling due to volcanic aerosol above 22 km (Figure 3) implies that the global increase of mean age of air (e.g., Figures 2a and 2d) is likely related to mixing effects. Figure 4 shows the decomposition of globally averaged deseasonalized mean age variability into the residual circulation transit time (RCTT), representing the pure residual circulation effect on mean age, and into aging by mixing, the eddy mixing effect integrated along the residual circulation, following Ploeger, Abalos, et al. (2015) (see supporting information). Directly following the Pinatubo eruption in June 1991, mean age increases significantly throughout the stratosphere above about 20 km (Figure 4a). This increase in mean age can be attributed to both increasing RCTT and increasing aging by mixing, with the RCTT contribution stronger at higher levels above about 22 km (Figures 4b and 4c) and the aging by mixing contribution stronger at all levels. Note that the RCTT represents the integrated residual circulation effect, whereas the $\overline{w}^*$ estimate from the latitudinal age gradient (see above) is a local quantity. Therefore, the increasing RCTT above about 22 km is not in contradiction with the increasing $\overline{w}^*$ estimated from the age latitudinal gradient (Figure 3) but rather indicates that decreasing upwelling at lower levels and pathway changes dominate the RCTT effect. The substantial simultaneous increase in RCTT and aging by mixing indicates a potential link between the integrated mixing effect

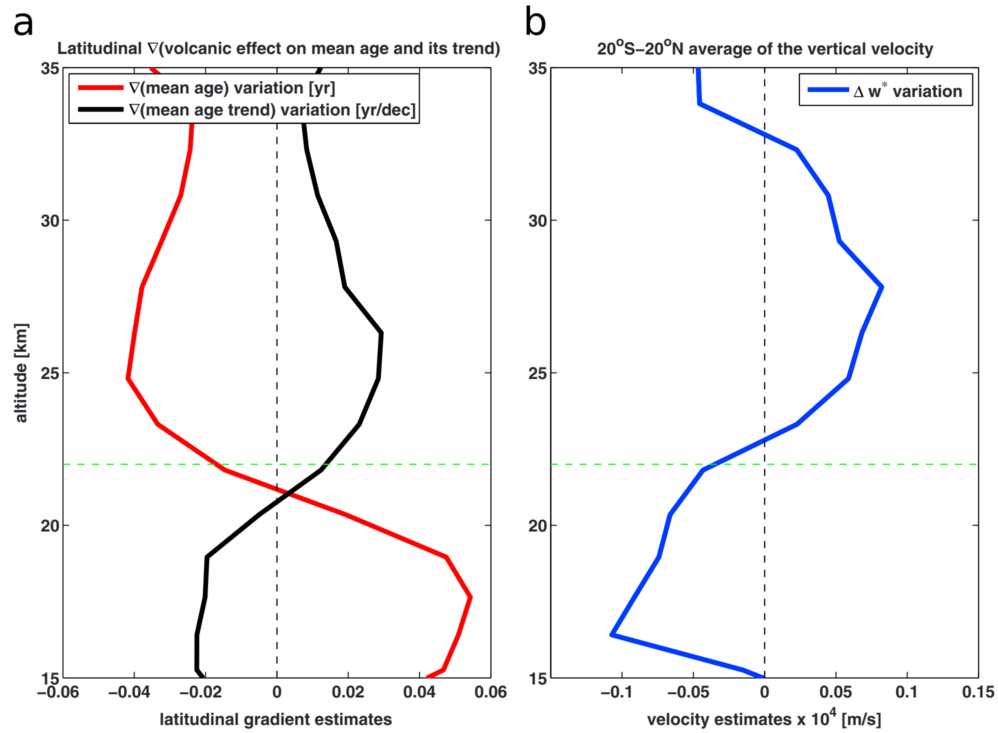

Figure 3. Vertical profiles of latitudinal gradient of the net volcanic effect on mean age, its trends, and $\overline{w}^*$. (a) The vertical profile of the latitudinal gradient of the net volcanic effect on mean age (red) and its trend (black) calculated from Figures 2a and 2d and averaged between the Northern and Southern Hemispheres. (b) Vertical profile of the net volcanic effect on the residual vertical velocities estimated from both standard formula ($\overline{w}^*$) between 20°S and 20°N over the 1989–2012 period. Green dashed line indicates the altitude 22 km.

and residual circulation changes, as discussed in previous studies (Garny et al., 2014; Pitari et al., 2016; Ray et al., 2014). Changes in the local mixing tendency below about 20 km (not shown) suggest a direct response of eddy mixing to volcanic aerosols at lower levels. Below about 20 km, the decrease in mean age initiated before the Pinatubo eruption extends up to 6 months after eruption. The related decrease in RCTT suggests increasing tropical upwelling directly after the eruption.

Increasing mean age in the tropical lower stratosphere related to volcanic aerosols from reanalysis is consistent with a recent modeling study. Muthers et al. (2016) show increasing mean age in response to volcanic eruptions in the tropical lower stratosphere (20°S–20°N at 63 hPa) and decreasing mean age in the middle and upper stratosphere in Northern Hemisphere high latitudes (60°–90°N at 16 hPa). Focussing on higher altitudes, other modeling studies also reported mainly decreasing mean age following volcanic eruptions (Garcia et al., 2011; Garfinkel et al., 2017). Similarly, Pitari et al. (2016) found decreasing mean age at higher levels of 30 hPa in the tropics and 10 hPa in the middle latitudes after the Pinatubo eruption. Hence, the response of the shallow BD circulation branch appears qualitatively consistent between ERA-Interim reanalysis and climate models (e.g., SOCOL, Muthers et al., 2016), while the response of the deep branch differs (Garcia et al., 2011; Garfinkel et al., 2017; Muthers et al., 2016). The main difference between the reanalysis and the models' response concerns the depth and strength of the deep versus shallow branch changes. In the reanalysis, the increase of mean age is stronger and reaches higher into the midstratosphere, while in the climate models it is confined to the lower stratosphere. Toohey et al. (2014) found the high-latitude response to be indirectly related to the volcanic heating through changes in wave propagation. Hence, differences in wave propagation (and mixing) between different models are expected to cause differences in the models' circulation response to volcanic eruptions, likely involving a strong role of internal variability, which is also important to the mechanism for changing age (see the ensemble spread in Figure 3 of Toohey et al., 2014).

We note that ERA-Interim and JRA-55 reanalyses do not explicitly assimilate volcanic aerosols. The effect of volcanic aerosols in the reanalysis is entirely related to the assimilation of observed temperatures (Fujiwara et al., 2015), which also constrains the wind response through thermal wind balance. Because of the missing direct

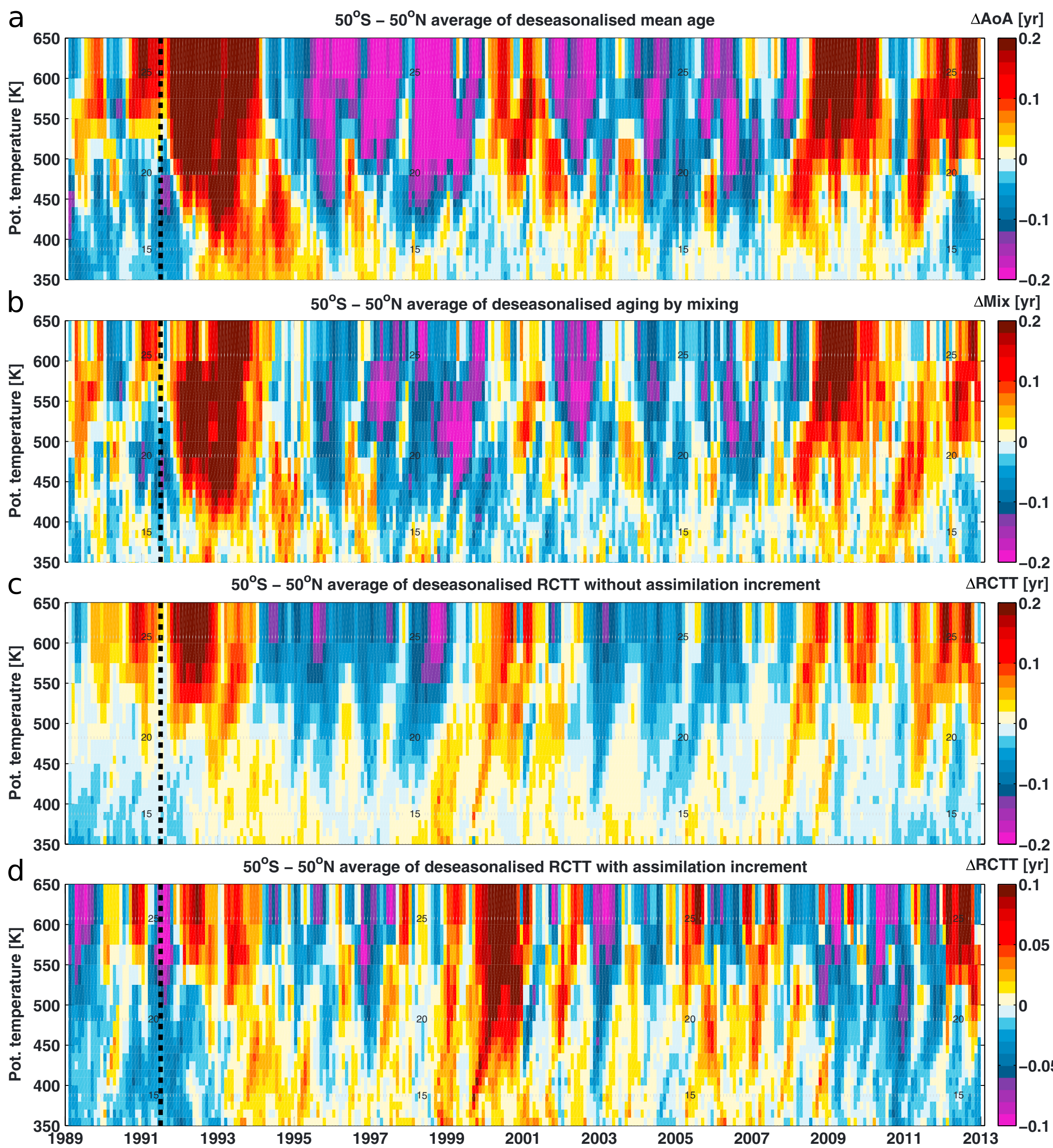

Figure 4. Globally deseasonalized time series of the (a) mean age, (b) aging by mixing, and (c and d) residual circulation transit time. Shown are the effects on mean age, aging by mixing, and residual circulation transit time (Figure 4c) without and with (Figure 4d) including assimilation increment related to volcanic eruptions since Pinatubo during the period 1989–2012. The decadal effects are calculated as a residual of the multiple linear regression without including the volcanic AOD signal. Black dashed lines show the height.

aerosol heating, the model underestimates stratospheric temperatures after the eruption and the induced assimilation increment tends to warm the model to fit the observations (see Figure S5). The magnitude of this missing diabatic heating contribution can be estimated from the assimilation increment (see Fueglistaler et al., 2009, for details on calculating the assimilation increment) although the increment includes also other factors. The assimilation increment due to the direct aerosol heating effect is found to enhance the total diabatic heating by about 20% directly following the eruption. It progressively decreases after about 6 months following the eruption (Figure S5a). For the interannual variability, adding the assimilation increment reduces the volcanic signal in the total diabatic heating rate by about 50%, but a significant weakening of tropical upwelling after Pinatubo eruption remains (see Figure S5b). Consequently, including the assimilation increment in the calculation of the RCTT reduces the aging above about 20 km and increases the freshening below right after the eruption (Figure 4d). During the first months after the eruption, the simulation with assimilation

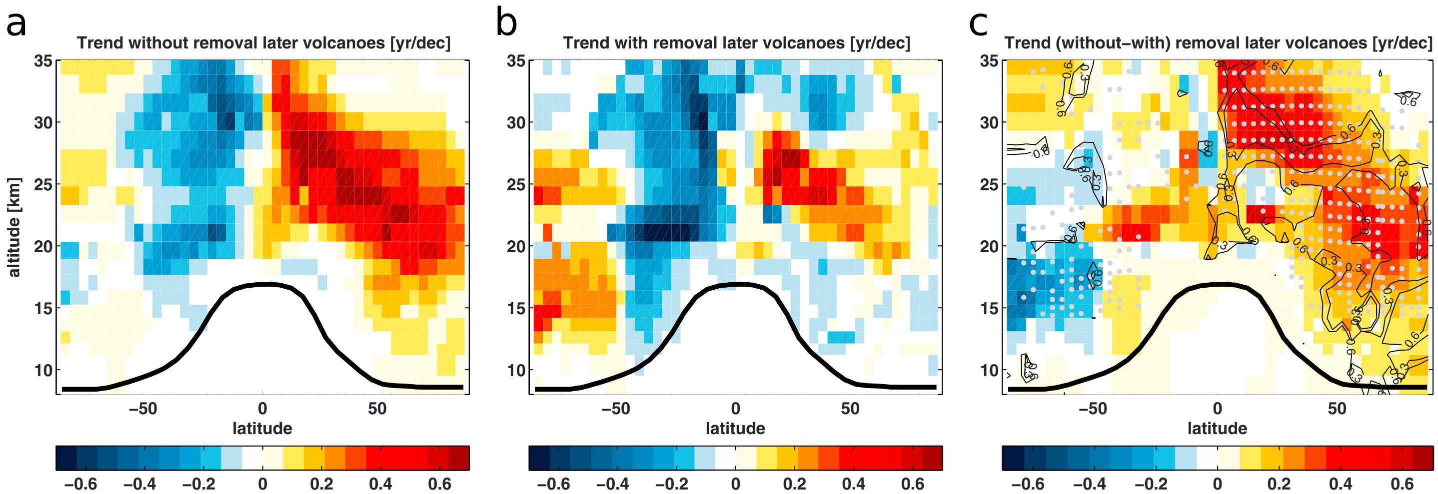

Figure 5. Zonal mean distribution of the volcanic aerosol contribution to the decadal mean age trends. Shown are the effects on mean age trends related to the later volcanoes during the period 2002–2011. The decadal mean age changes are calculated as a linear trend from the multiple linear regression (a) without explicitly including the volcanic AOD signal and (b) with including the volcanic signal. (c) The difference between the two quantities (without-with) is by definition the volcanic effect on the mean age trends. Figure 2c contours show the fractional change of the trend between Figure 2a and Figure 2b. Gray dots indicate statistical significance at the 95% level estimated from a Student's *t* test.

increments shows even a strong freshening at upper levels (above about 22 km). Therefore, adding the assimilation increment to the heating rate brings the reanalysis-driven simulation closer to the climate model results. However, even with adding the assimilation increment to correct for the missing direct aerosol heating in the reanalysis, a clear aging after the Pinatubo eruption remains, corroborating our conclusions. Furthermore, reanalysis products may suffer from changes in the assimilated observational data sets (e.g., the introduction of Advanced Microwave Sounding Unit-A data (Dee & Uppala, 2009) in 1998 and of radio occultation data (Poli et al., 2010) at the end of 2006). However, the good agreement between mean age trends from simulations driven by meteorological reanalysis with observations found in previous work provides confidence in the reliability of simulated stratospheric circulation changes (Ploeger, Riese, et al., 2015).

Additionally, Figure 4a shows a significant increase of mean age starting in 2008. This increase in globally averaged mean age can be traced back to a distinct hemispheric trend pattern, with strongly increasing mean age in the Northern Hemisphere and decreasing mean age in the Southern Hemisphere (see Ploeger, Riese, et al., 2015 for details). The pattern of these circulation changes qualitatively agrees with satellite observations and is related to decadal variability (Haenel et al., 2015). Figure 5 shows the effect of the minor volcanic eruptions after 2008 on the stratospheric circulation estimated from the 2002–2011 mean age time series. These minor volcanoes shows a persistent AOD signal in the extratropical lowermost stratosphere (Figure 1a). A multiple linear regression including the observed AOD signal only after 2008 was used to better isolate the effect of extratropical volcanoes and the remaining contributions in the AOD time series set to a background value of 0.0046 nm. Although the post-2008 eruptions are clearly weaker than Pinatubo, the regression method yields a significant aging related to these minor eruptions (see Figure 5c). Remarkably, the volcanic aerosol related effect after 2008 shows a significant increasing mean age in the extratropical lower stratosphere in the Northern Hemisphere and decreasing mean age in the high-latitude Southern Hemisphere during the 2008–2011 period. The strongest impact of the post-2008 eruptions on mean age occurs in the Northern Hemisphere lower stratosphere coinciding with the region of highest extratropical volcanic aerosol loading due to these volcanoes (Andersson et al., 2015; Vernier et al., 2011). Parts of the volcanic plumes of Okmok, Kasatochi, Sarychev, and Nabro were, however, horizontally transported from the extratropical Northern Hemisphere into the tropics (Bourassa et al., 2010; Haywood et al., 2010), where they were slowly lofted within 1 year up to about 25 km. Based on the regression, we hypothesize that the post-2008 minor eruptions significantly change the resulting decadal trend in mean age for the 2002–2011 period (Figure 5c). In large regions of the Northern Hemisphere the slowdown of the stratospheric circulation between 2002 and 2011 can be attributed to the recent minor volcanic eruptions after 2008. The remaining decadal trend in mean age can likely be associated with a southward shift of the stratospheric circulation, as suggested by Stiller et al. (2017). Moreover, potential links between volcanic aerosol effects and stratospheric circulation shift could exist.

Note that decadal mean age changes during 2002–2011 in JRA-55 show a different hemispheric pattern as compared to ERA-Interim and MIPAS observations (not shown), but a similar increase in mean age related to minor volcanic eruptions (Figures 1d and S1d), suggesting that volcanic aerosols are not causing the differences between the two reanalyses.

4. Summary and Conclusions

We have estimated the effect on the stratospheric circulation of increases in stratospheric aerosol loading due to volcanic eruptions via mean age of air and its trends. Mean age of air from model simulations consistent with observations for the 1989–2012 period has been analyzed using a multiple linear regression technique accounting for observed stratospheric aerosol. We find that a substantial contribution in decadal variability of the stratospheric circulation, as represented by variability in mean age of air, is caused by volcanic aerosol injections. Pinatubo clearly stands out impacting the global stratosphere immediately after the eruption. The volcanic aerosol effect on tropical upwelling in the meteorological reanalysis turns out to be qualitatively consistent with climate model results, showing strengthened tropical upwelling at upper levels (above about 22 km) and weakened tropical upwelling below (see Figure 3). The mean age response, however, is not unambiguously linked to the tropical upwelling change and shows increasing mean age of air globally, whereas climate models show decreasing mean age at upper levels (e.g., Garcia et al., 2011; Garfinkel et al., 2017; Muthers et al., 2016). We find the mean age increase after volcanic eruptions significantly affected by volcanically induced mixing effects. A substantial increase in aging by mixing appears to be related to both an increase in mixing tendency and a slowdown of the residual circulation.

In summary, the main difference between the meteorological reanalyses and climate models' responses concern changes in the depth and strength of the deep versus shallow branch of the stratospheric circulation. In the meteorological reanalyses, the increase of mean age is stronger and reaches higher into the midstratosphere, while in the climate models it is confined to the lower stratosphere (Muthers et al., 2016).

Minor volcanic eruptions after 2008 also show a distinct effect on the stratospheric circulation in the Northern Hemisphere stratosphere, significantly impacting the pattern of decadal mean age variability and its trends during 2002–2011 (Figure 5c). Increases in volcanic aerosol loading after 2008 are not included in current model simulations of recent climate change (Santer et al., 2014; Solomon et al., 2011). We speculate that the inadequate representation of volcanic aerosol forcing, in combination with the lack of a reliable representation of natural variability (e.g., wave propagation, mixing, QBO, and aerosol forcing) could be the reason why current climate models fail in simulating the observed pattern of the stratospheric circulation change over the past few decades in the Northern Hemisphere. The effect on the stratospheric circulation due to volcanoes found here will likely carry over to geoengineering scenarios based on sulfate aerosols injections into the stratosphere (Aquila et al., 2014; Tilmes et al., 2015).

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