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# Significant contributions of volcanic aerosols to decadal changes in the stratospheric circulation

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The stratospheric circulation is an important element of climate as it determines the concentration of radiatively active species like water vapour 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 focussing on the Mt. 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 erup-

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tions, including the minor eruptions after 2008, for a reliable reproduction of  
observed stratospheric circulation changes.

Accepted Article

## 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<sub>2</sub>O, CH<sub>4</sub> and O<sub>3</sub>, as well as the amount of stratospheric water vapour [Solomon *et al.*, 2010; Riese *et al.*, 2012] 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; Ray *et al.*, 2014; Mahieu *et al.*, 2014; Haenel *et al.*, 2015], constituting an uncertainty in current climate simulations. Recent model simulations [Diallo *et al.*, 2012; Ploeger *et al.*, 2015a] 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 speed up. 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., QBO, ENSO, 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<sub>2</sub>) oxidized to sulfuric acid (H<sub>2</sub>SO<sub>4</sub>), which then conden-

sates to form a layer of fine sulphate aerosol droplets ( $\text{H}_2\text{SO}_4/\text{H}_2\text{O}$ ) also known as the Junge Layer [Junge and Manson, 1961]. In particular during the major eruption of Mt. 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) [Vernier *et al.*, 2011; Fromm *et al.*, 2014; Andersson *et al.*, 2015]. 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 [Schmidt *et al.*, 2014; Santer *et al.*, 2014; Huber and Knutti, 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 T1 in the supplement). 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 Sect. 2.2 for a definition) and observational stratospheric AOD from satellites. We used mean age calculated with CLaMS [Ploeger *et al.*, 2015a] 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] reanalysis 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 and Plumb, 1994]. Further details about the CLaMS model and the specific simulation are described by Pommrich *et al.* [2014] and Ploeger *et al.* [2015a]. For comparison, we consider mean age calculations from the Lagrangian trajectory model, TRACZILLA [Legras *et al.*, 2005], using the set-up described by Diallo *et al.* [2012, 2017]. Both CLaMS and TRACZILLA mean age simulations have been thoroughly validated with balloon-borne measurements and MIPAS satellite observations of CO<sub>2</sub> and SF<sub>6</sub>, giving confidence in their robustness [Diallo *et al.*, 2012; Ploeger *et al.*, 2015a]. 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) as for the long-term weak increase of mean age in the northern hemisphere upper stratosphere [*Diallo et al.*, 2012; *Ploeger et al.*, 2015a].

### 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–May 2006) and on CALIPSO (CloudSat and the Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation) (June 2006–December 2012) measurements (red line in Fig. 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 [*Vernier et al.*, 2011; *Sato et al.*, 1993]. 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 and 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 dis-

cernible 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 timeseries 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; Haywood *et al.*, 2010; Carn *et al.*, 2016] (see Table T1). 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 one year. These post–2008 eruptions persistently enhanced the Junge layer in the extratropical lowermost stratosphere [Vernier *et al.*, 2011; Andersson *et al.*, 2015].

### **3. Effect of volcanoes on mean age and its trend**

A common metric of the stratospheric circulation is the mean age of stratospheric air [Vaughan and 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 deseasonalised mean age during the Pinatubo pe-

riod. 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 (1) in the Method section in the supplement, 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 space-borne observations [Ploeger *et al.*, 2015a]. 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 timeseries from merged satellites measurements [Vernier *et al.*, 2011] were used in the multiple linear regression model.

Figure 1(c,d) depicts the residual from the regression ( $\epsilon$  in equation (1) in the supplement) with and without removal of the AOD signal related to all volcanic eruptions from the mean age. Without removing the AOD signal (blue and black dashed line), the variability in the

residual closely follows the variability in the deseasonalised mean age (Fig. 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 Figure 1(c,d)). Remarkably, including the volcanic aerosol signal in the multiple linear regression substantially reduces the globally averaged mean age linear trend from  $-0.16$  yr/dec (without including the AOD signal) to  $-0.12$  yr/dec, i.e. 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 cancelled 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 (Fig. 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 (1) normalised by the standard deviation ( $STD$ ) of the AOD. The dominant signal in the whole AOD timeseries is associated with the Pinatubo eruption. The figure shows evidence for an increase of mean age by up to 0.25 yr throughout the lower and mid stratosphere following the eruption. (Fig. 2a). The results shown here are based on CLaMS and are analogously reproduced for TRACZILLA simulations in the

supplement (Fig. 2S). This increase of the mean age did not occur instantaneously but evolved in time as shown in Fig. 3S. 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 (Fig. 1b and Fig. 3S). 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) (Fig. 4Sa). The difference between the standard deviation of the residual ( $\epsilon$  in equation (1) in the supplement) 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 (Fig. 4Sb). This changing pattern in the residual is similar to the explicitly calculated volcanic effect for the Pinatubo period (Fig. 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 supplement. 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 mid stratosphere in Fig. 2, which is mainly dominated by the Pinatubo eruption, is statistically robust.

Figure 2(b-d) shows the stratospheric circulation changes, measured in terms of mean age trends (linear term  $a$  in equation (1) in the supplement), for the 1989–2012 period, without (Fig. 2b) and with (Fig. 2c) removing the volcanic aerosol signal in the multiple linear regression. Note that a negative mean age trend corresponds to a speed up of the stratospheric circulation and a positive mean age trend to a slow-down. For the 1989–2012 period, the calculation without including the AOD term in the multiple linear regression (Fig. 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 (Fig. 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 (Fig. 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 yr/dec (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  $\bar{w}^*$  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,  $\Delta\Gamma \sim 1/\bar{w}^*$ , 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 (Fig. 3a) as well as the  $\bar{w}^*$  estimate (Fig. 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  $\Delta\Gamma \sim 1/\bar{w}^*$ ) and decreasing upwelling below. This result agrees well with the  $\bar{w}^*$  estimate, which shows an increasing tropical upwelling at the upper levels and decreasing upwelling at the lower levels related to volcanic aerosol (Fig. 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 (Fig. 3a). This implies a negative volcanic effect on the trend of the tropical ascent rate (noting  $d(\Delta\Gamma)/dt \sim -d\bar{w}^*/dt$ ).

The clear increase of tropical upwelling due to volcanic aerosol above 22 km (Fig. 3) implies that the global increase of mean age of air (e.g., Fig. 2(a,d)) is likely related to mixing effects. Figure 4 shows the decomposition of globally averaged deseasonalised 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 et al.* [2015b] (see supplement). Directly following the Pinatubo eruption in June 1991, mean age increases significantly throughout the stratosphere above about 20 km (Fig. 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 (Fig. 4(b, c)) and the aging by mixing contribution stronger at all levels. Note that the RCTT represents the integrated residual circulation effect whereas the  $\bar{w}^*$  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  $\bar{w}^*$  estimated from the age latitudinal gradient (Fig. 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 and residual circulation changes, as discussed in previous studies [Garny *et al.*, 2014; Ray *et al.*, 2014; Pitari *et al.*, 2016]. 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 re-analysis is consistent with a recent modelling 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 mid and upper stratosphere in northern hemisphere high latitudes (60°–90° N at 16 hPa). Focussing on higher altitudes, other modelling 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 re-analysis and climate models [e.g. SOCOL, Muthers *et al.*, 2016], while the response of the

deep branch differs [Garcia *et al.*, 2011; Muthers *et al.*, 2016; Garfinkel *et al.*, 2017]. 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 mid stratosphere 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 Fig. 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 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 Fig. 5S). 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 (Fig. 5Sa). For the inter-annual 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 Fig. 5Sb). 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 (Fig. 4d). During the first months after the eruption, the simulation with assimilation 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 datasets (e.g., the introduction of AMSU-A data [Dee and 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 et al., 2015a].

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 et al. [2015a] 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 timeseries. These minor volcanoes shows a persistent AOD signal in the extratropical lowermost stratosphere (Fig.

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 timeseries 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 Fig. 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 [Vernier *et al.*, 2011; Andersson *et al.*, 2015]. 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 one 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 (Fig. 5c). In large regions of the northern hemisphere the slow-down of the stratospheric circulation between 2002–2011 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 erup-

tions (Fig. 1d and Fig. 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 analysed 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 Fig. 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]; *Muthers et al.* [2016]; *Garfinkel et al.* [2017]). 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 slow-down 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 mid stratosphere 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 (Fig. 5c). Increases in volcanic aerosol loading after 2008 are not included in current model simulations of recent climate change [*Solomon et al.*, 2011; *Santer et al.*, 2014]. 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, 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 sulphate aerosols injections into the stratosphere [*Aquila et al.*, 2014; *Tilmes et al.*, 2015].

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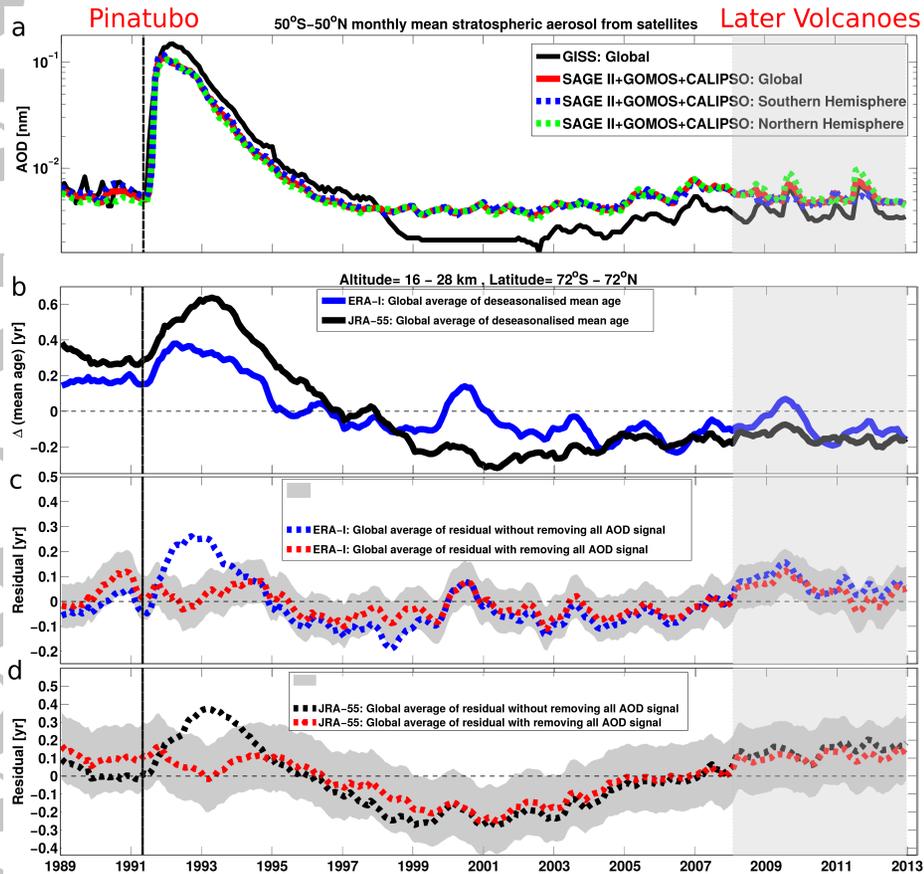
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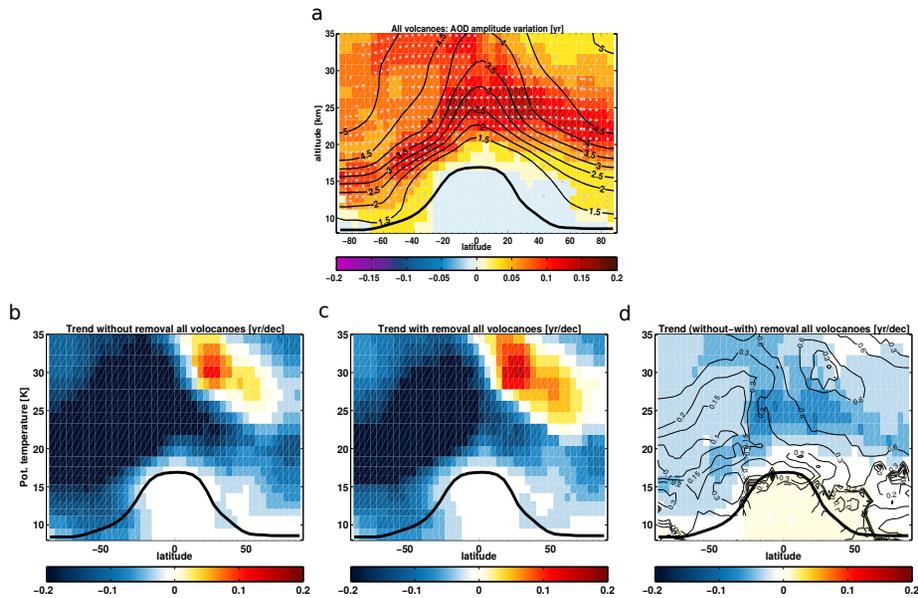
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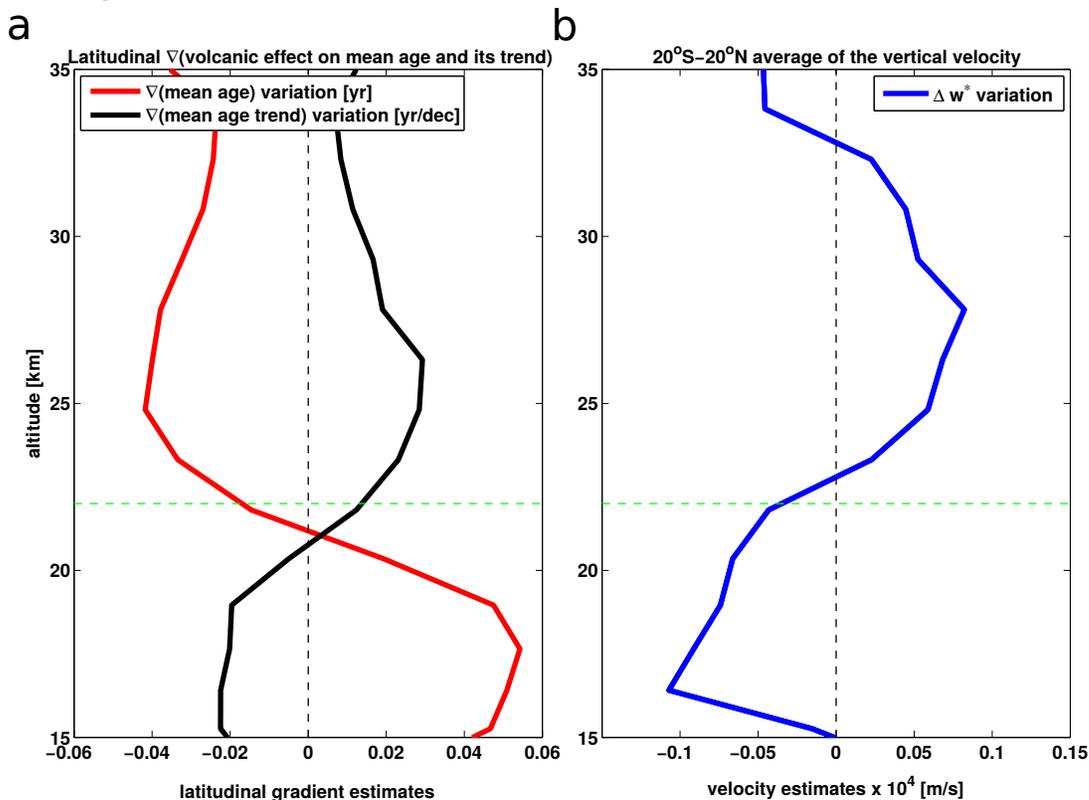
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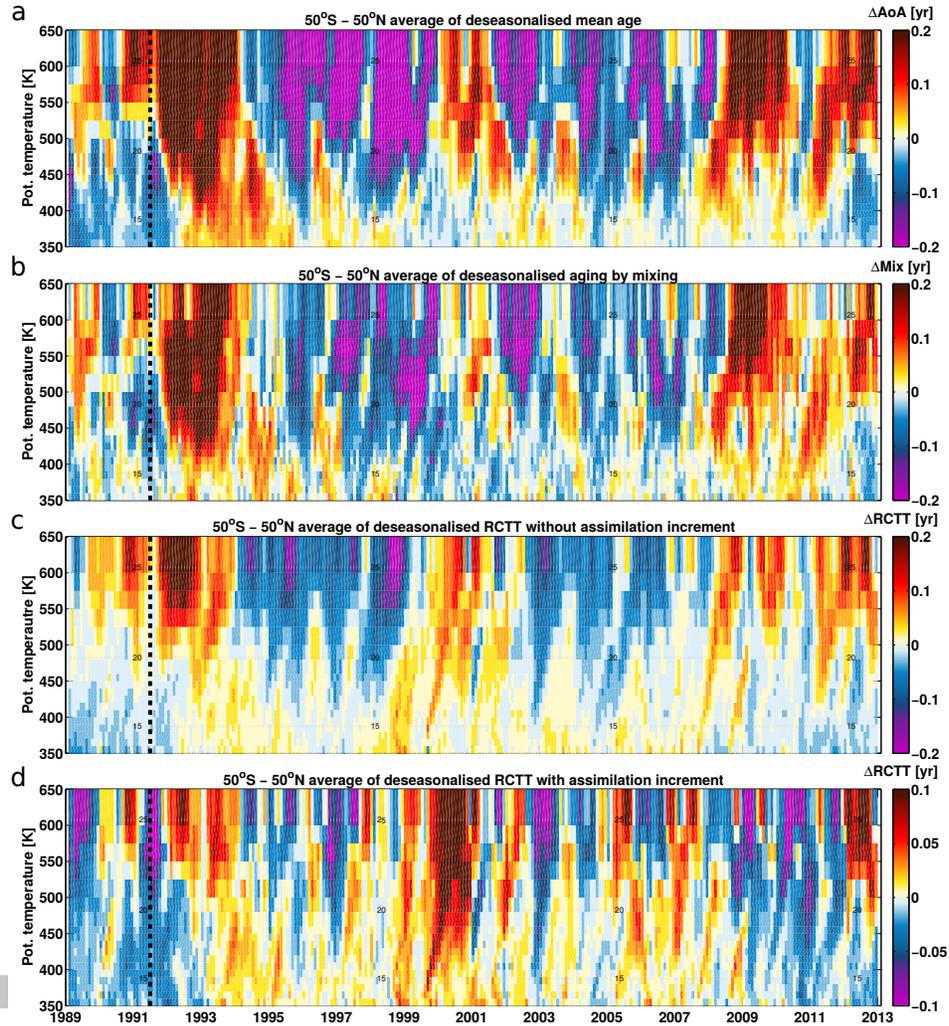
**Figure 1.** Globally averaged timeseries of the stratospheric AOD, deseasonalised mean age and residual of the multiple linear regression with and without removal of all AOD signal. (a) Stratospheric AOD timeseries is averaged from 50°S–50°N over the 1989–2012 time period and is shown for merged satellites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



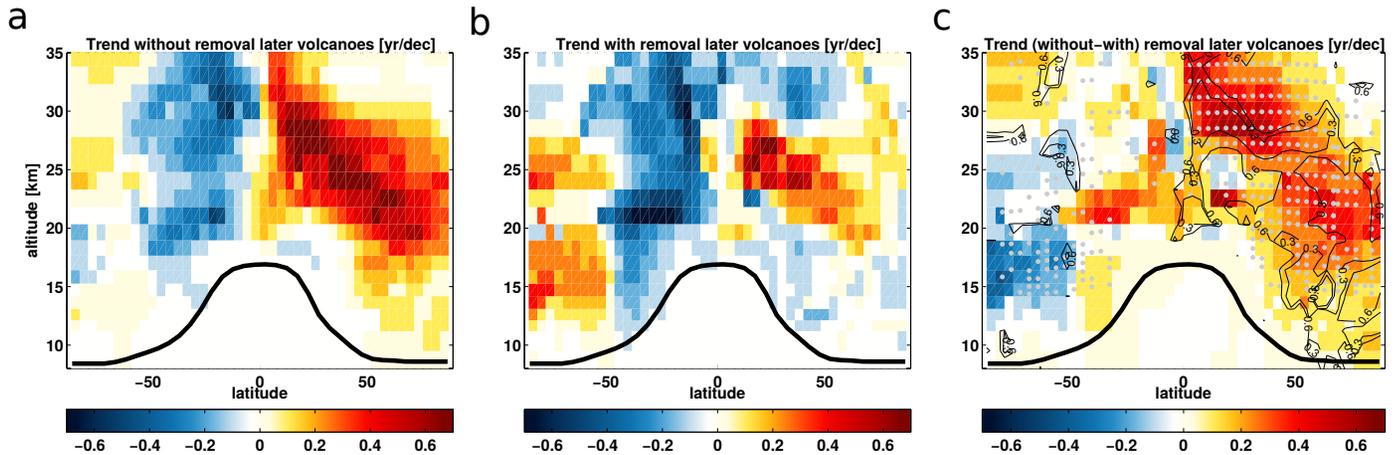
**Figure 2.** Zonal mean distribution of volcanic aerosol effect on mean age (a) and its decadal trends (b-d). The amplitude of the mean age variations (term  $b_3 \times STD(aod)$ ) attributed to the volcanic aerosol from all eruptions since Pinatubo eruption are calculated by using AOD signal from 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 (b) and with including the AOD signal (c). The difference between the two quantities (without-with) is by definition the volcanic effect on the mean age trends (d). 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. Fig. 2d contours show the fractional change of the trend between Fig. 2c – Fig. 2b.



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



**Figure 4.** Globally deseasonalised timeseries of the mean age (a), aging by mixing (b) and residual circulation transit time (c-d). Shown are the effects on mean age, aging by mixing and residual circulation transit time (c) without and with (d) 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.



**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 (a-c). The decadal mean age changes are calculated as a linear trend from the multiple linear regression without explicitly including the volcanic AOD signal (a) and with including the volcanic signal (b). The difference between the two quantities (without-with) is by definition the volcanic effect on the mean age trends (c). Fig. 2c contours show the fractional change of the trend between Fig. 2a – Fig. 2b. Gray dots indicate statistical significance at the 95% level estimated from a Student’s t-test.