Australian Wildfires Cause The Largest Stratospheric Warming Since Pinatubo.

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Abstract

Global mean lower stratosphere temperatures rose abruptly in January 2020 reaching values not experienced since the early 1990s. Anomalous lower stratospheric temperatures were recorded for 4 months at highly statistically significant levels (p-values of 0.0004 to 0.02). While the warming event of 1991-1993 has been definitively attributed to absorption of sunlight by stratospheric sulfate from the eruption of Pinatubo, no candidate volcanic eruption for explaining the 2020 stratospheric heating exists. Here, we use a combination of satellite and surface-based remote sensing observations to derive a time-series of stratospheric biomass burning aerosol optical depths originating from intense S.E. Australian wildfires and apply these aerosol optical depths to a state-of-the-art climate model. We show beyond doubt that the S.E. Australian wildfires are the cause of this lower stratospheric warming with implications for stratospheric dynamics and stratospheric ozone should this type of event become more frequent in the future.

1. Introduction:

Sulfate aerosols originating from explosive volcanic eruptions are periodically injected into the stratosphere, where they cause a cooling of climate by scattering incident sunlight back to space (e.g., Angell and Korshover, 1984; Hansen et al., 1992; Soden et al., 2002). Sulfate aerosols also absorb sunlight at infra-red wavelengths (e.g. Dykema et al, 2016) causing stratospheric heating, as evident in observations subsequent to the eruptions of El Chichon and Pinatubo (e.g. Labitzke, 1983; Angell, 1993; 1997). Satellite-based instruments reveal that, with the exception of the periods influenced by El Chichon and Pinatubo, the lowermost stratosphere cooled by around 1 K between 1979 and 1995 but has since remained approximately constant, primarily owing to reductions in anthropogenic emissions of ozone depleting substances (e.g. Arblaster et al., 2014; Maycock et al., 2018; Steiner et al., 2020). State-of-the-art climate models are able to represent both the long-term trend in stratospheric temperature and the sporadic heating of the stratosphere caused by the eruptions of El Chichon and Pinatubo with reasonable fidelity (e.g. Maycock et al., 2018).

Sulfate aerosols from explosive volcanic eruptions are not the only source of stratospheric aerosols. There is increasing evidence of stratospheric intrusions of biomass burning aerosol (BBA, commonly referred to as smoke) from intense pyrocumulonimbus (pyroCb) events from wildfires (e.g. Fromm et al., 2000; 2005; Peterson et al., 2018; Christian et al., 2019). The 2019-2020 December-January-February (DJF) Australian 'Black Summer' wildfires were unprecedented; the scale, intensity and impacts were all unmatched in the historical record (Abram et al., 2021) with over 5.8 million hectares burned (Boer et al., 2020). Extreme drought caused the exceedance of critical flammability thresholds for the most prolonged period during the last 30 years (Boer et al., 2020) allowing the unconstrained spread of fires (Abram et al., 2021) which resulted in millions of tonnes of smoke and associated gases being injected into the upper troposphere and lower stratosphere (UTLS; Hirsch and Koren, 2021). The strongest pyroCb outbreak occurred on 31 December 2019 (Khaykin et al., 2020), with initial injection altitudes reaching as high as 16km (Kablick III et al., 2020). The smoke plumes formed several vortices (Khaykin et al., 2020), the

largest of which maintained a coherent and isolated structure for over 2 months (Kablick III et al., 2020; Supplemental Figure 1) and was eventually detected at altitudes of up to 36km (Khaykin et al., 2020). The ascent of the aerosol particles to the remarkably high altitudes is a result of the self-lofting caused by the strong solar absorption of the black carbon (BC) component of the smoke particles (Yu et al., 2019; 2021). Figure 1 shows CALIOP-derived vertical profiles of attenuated backscatter at 532nm and aerosol sub-type for various locations across the South Pacific as the aerosol plume evolves (Supplemental Figure S1). Over the period of a month, the aerosol plume drifted across the South Pacific and was clearly detected in the stratosphere by CALIOP and surface-based lidars and sun-photometers operating from the southern tip of South America (Ohneiser et al., 2021).

By combining satellite-based observations of BBA with surface-based remotely sensed observations of aerosol microphysical properties and utilising a state-of-the-art climate model, we go beyond recent studies (e.g. Stocker et al., 2021; Ohneiser et al., 2021; Yu et al., 2021; Peterson et al., 2021) to show beyond reasonable doubt that the substantial absorption associated with the BBA from the SE Australian fires caused the largest lower stratospheric warming since the eruption of Pinatubo.

2. Results:

We use two satellite datasets to characterize the perturbation to stratospheric aerosol in the southern hemisphere, following the Black Summer fires. The CALIOP sensor onboard the CALIPSO satellite (e.g. Winker et al., 2009; Figure 1) and the Ozone Mapping Profiler Suite (OMPS) Limb-Profiler (LP) (OMPS-LP) onboard the Suomi National Polar-orbiting Partnership satellite (Flynn et al., 2014; Chen et al., 2018) are proven instruments for detecting stratospheric smoke aerosols (e.g. Torres et al., 2020, Peterson et al., 2021, Christian et al., 2019). The perturbations to stratospheric aerosol optical depth (SAOD) above the long-term means are presented in Figure 2 (see Methods, M1-M3). It is immediately obvious that the two satellite datasets have different temporal evolutions. The CALIOP SAOD peaks at around 0.015 some two weeks after the initial pyroCb outbreak occurred. Such a delay from initiation might be expected because there were several periods of intense fires over the first few weeks of 2020, which could continue to load the stratosphere, and because aerosol injected into the upper troposphere might only enter the stratosphere subsequent to self-lofting. After this peak, the CALIOP SAOD decays rapidly because as the smoke becomes more dilute, the minimum detection thresholds for the night-time retrievals of aerosol extinction coefficient are not reached (0.012 km^{-1} , Rogers et al., 2014) leading to under-detection. As a dedicated stratospheric limb-profiler, OMPS-LP has a much lower minimum detection threshold and the SAOD reaches a maximum in early February before decaying at a much-reduced rate compared to CALIOP. Quantitative comparisons between OMPS-LP and CALIOP during the initial stage of the smoke plume suggest that, in common with other limb-instruments, OMPS-LP may fail to detect a portion of the plume that is close to the tropopause (e.g. Fromm et al., 2014), although this issue appears a relatively minor concern in this study as the aerosol reaches high altitudes. We derive a composite SAOD (COMP) data set that combines aerosol extinction from both sensors and interpolates OMPS-LP data in latitudinal bands to account for missing data during the southern hemisphere summer (see

Methods). The resulting SAOD initially follows CALIOP up to its peak and is then linearly interpolated in the 'cross-over region' between the peak SAODs of the two instruments before following the OMPS-LP data. We estimate a mass of BBA in the stratosphere of approximately 0.55 Tg derived from the peak of the SAOD measurements using a specific extinction at 532nm for BBA of $4.8\text{m}^2\text{g}^{-1}$. This estimate is almost mid-way between those from previous estimates that range from 0.2 Tg to 3.1 Tg (Hirsch and Koren, 2021; Kablick III et al., 2020; Khaykin et al., 2020; Yu et al., 2021) and rivals that from the 2019 eruption of Raikoke which injected an estimated 0.9-1.1 Tg of SO_2 into the lower stratosphere (de Leeuw et al., 2021).

Figure 3 shows snapshots of the aerosol extinction derived from the COMP dataset at 2-week intervals to demonstrate the evolution of the smoke plume in the latitudinal-vertical plane. The first plot in the time series clearly identifies the initial injection of smoke that was observed to reach altitudes of 16km on 31 December 2019 (Khaykin et al., 2020; Kablick III et al., 2020) and was transported southeast from the region of emissions creating the peak in extinction seen at 40-50°S. The south-eastward movement of the initial plume is evident from the spatial analysis of the OMPS-NM nadir viewing instrument (Supplemental Figure S1). By the week commencing 12 January 2020, this is joined by another intense plume centered between 30-40°S as a result of further intense SE Australian fires. This plume intensifies (week commencing 26 January 2020) reaching peak values exceeding in the zonal mean at altitudes of around 16km between latitudes of 30-40°S. Subsequently, the plume spreads equatorward and dilutes significantly, but a zonal mean anomaly in aerosol extinction is still clearly evident for the week commencing 19 April 2020 (Figure 3) and extends throughout 2020 (Figure 2). There is also evidence of perturbations to aerosol extinction reaching altitudes of 25-35km, supporting the evidence shown in CALIPSO retrievals (Figure 1) and earlier analyses (Khaykin et al., 2021). Stocker et al. (2021) derived perturbations in aerosol extinction relative to a single month of OMPS-LP observations (December 2019) rather than relative to a long-term mean, but we note many similarities between their results and those shown here.

To estimate the impact that the aerosol perturbation has on lower stratospheric temperatures (LSTs), we apply the COMP extinction data to the UKESM1 climate model, which has a facility (Easy-Aerosol) for imposing distributions of aerosol optical properties (see Methods, M4). To extend the extinction into full wavelength-dependent optical properties we assume an aerosol size distribution derived from AERONET observations over Punta Arenas in southern Chile when the aerosol was clearly impacted by the aerosol optical depths (Figure 1, Ohneiser et al., 2021). We assume the refractive indices derived from recent intensive measurements of aged biomass burning aerosol (Peers et al., 2019). Mie scattering calculations reveal a single scattering albedo at 550nm of 0.86, which is representative of aerosol with strong absorption characteristics as inferred from co-located lidar measurements (Ohneiser et al., 2021). The absorption properties of BBA in the troposphere have been the subject of much scrutiny in recent international field campaigns (e.g. Haywood et al., 2021; Redemann et al., 2021, Zuidema et al., 2016) and depend on the combustion sources, the degree of flaming and smoldering combustion, age dependent oxidation, bleaching of organic components, and the collapse of black carbon chain structures

(e.g. Haywood et al., 2021). The optical properties associated with UTLS smoke are even more uncertain (e.g. Yu et al., 2019). However, a single scattering albedo of 0.86 at a wavelength of 0.55 μm agrees with lidar derived estimates of 0.8-0.9 for aged boreal UTLS smoke (Hu et al., 2019; Haarig et al., 2018; Ohneiser, et al., 2020; 2021).

The model simulations comprise 10 pairs of simulations with UKESM1 with each pair including a control simulating present-day climate (CNTL) and a parallel simulation starting from the same initial conditions but including the aerosol perturbation (COMP). Each pair ran for 12 months and used a unique set of initial conditions to create an ensemble of results. The radiative heating associated with the aerosol perturbation peaked at around 0.2 K/day (Supplemental Figure S2) and the resulting perturbations to monthly-mean stratospheric temperatures are shown in Figure 4 as zonal averages for the ensemble.

Statistically significant increases in LSTs (at 5% significance level) develop across much of the southern hemisphere and persist through January - June. The warm anomalies peak during February and reach around 3K at pressures of between 50-100hPa (16km-20km). While generally, the maximum LST perturbations are associated with the maximum in aerosol extinction, significant poleward LST perturbations are noted in February and March together with evidence of equatorward heating of the LST at lesser statistical significance. Remote temperature perturbations have been found in other model experiments that injected aerosol at 30°S to replicate the impacts of hypothetical geoengineering schemes (Richter et al., 2017, their Figure 1e). This latitudinal spread of the temperature response might be expected due to induced changes in stratospheric dynamics which can influence stratospheric ozone (e.g. Randel et al., 1995; Richter et al., 2017). However, it is the BBA, rather than temperature changes owing to ozone feedbacks, that are the dominant cause of the warm LST anomalies (Supplemental, S3).

To assess whether the modelled perturbation to the LST resembles reality, we examine observations from the Microwave Sounding Unit (MSU) channel 4 and Advanced Microwave Sounding Unit (AMSU) channel 9 retrievals that are sensitive to LSTs within the 13-22km altitude band (Maycock et al., 2018; Steiner et al., 2020), where the model temperature perturbation is largest (Figure 3). These instruments are chosen in preference to the Stratospheric Sounding Unit (SSU) as the minimum altitude of detection for the SSU channel 1 is around 25–35 km (pressures less than 20hPa) which is above the altitude of the maximum temperature perturbation derived from the model. To enable a fair comparison, the model temperature data has been vertically weighted in the same way as the MSU/AMSU data (Methods, M5). We compare the LST anomalies for MSU/AMSU and UKESM1 across the long-term record (1979-2020) and also more closely for 2020 and focus mainly on variations at the global scale (with near-global coverage from 83°S to 83°N), although results are also presented for sub-regions in the Supplementary Material (Figure S4).

Figure 5a-b shows that well-known features of the observed record are well-replicated in the climate model. The long-term mean cooling trend attributed to stratospheric ozone depletion (Arblaster et al., 2014; Maycock et al., 2018; Steiner et al., 2020) and the levelling off of that trend due to reduced anthropogenic emissions of ozone-depleting substances (ODS, e.g Ferraro et al., 2015; Engel et al., 2018) are well-represented. The observed time series is interrupted by two strong warming events associated

with the volcanic eruptions of El Chichon and Pinatubo, and is again well-represented by the UKESM1 climate model. In the observations (Figure 5a), a strong but brief warming event occurs at the beginning of 2020 and emerges as the highest spike in LST, since the aftermath of the eruption of Pinatubo in 1991. This warming event is not associated with the sudden stratospheric warming event of late 2019 (e.g. Rao et al., 2020; Yamazaki et al., 2020) but occurs as a separate and more significant anomaly during early 2020. The limited areal extent of the 2019 sudden stratospheric warming in southern hemisphere polar regions means that, while such an event is significant regionally, and even at hemispheric scales (Supplementary Figure S4), it becomes relatively insignificant at the global scale. Figure 5b shows that, as in the observations, the shorter duration uptick in modelled LSTs is evident as the largest since the aftermath of the Pinatubo eruption.

Figure 5c focuses on 2020 and shows the model experiment alongside the control simulations, that did not include the COMP BBA, together with the observations. The difference in LST between the experiment and control is statistically significant throughout February-May with p-values of 0.0023, 0.0004, 0.0007, and 0.0035 for each month (assuming a Students t-distribution) indicating that the perturbations in the temperatures are well outside those that occur naturally in the model. The perturbation of temperature reaches a maximum of around +0.7K in February-March in both the observations and the model. The stratospheric temperature in the COMP remained elevated above that in the control throughout 2020 but the differences are within the 95% confidence interval after May with p-values exceeding 0.1 in November and December. To elucidate reasons that the BBA is so effective at warming the UTLS, we perform Mie scattering calculations averaged across the solar spectrum for both BBA and for sulfate aerosol (Supplemental, S4). Sulfate aerosol only absorbs significant solar radiation for wavelengths exceeding around 1.3microns (e.g. Dykema et al., 2016), while BBA absorbs across all solar wavelengths. Our calculations suggest that BBA is approximately 50 times more absorbing than sulfate aerosol, and thus highly effective at heating the stratosphere.

While the UKESM1 model is in remarkable agreement with the observations when the BBA is included within the model for the first four to five months of 2020, it does not replicate the intense cooling that peaked in November 2020 (Figure 5; Supplemental, S5). Reasons for these differences are not clear but could be because the UKESM1 simulations do not include heterogeneous chemistry that typically leads to reductions in stratospheric ozone at polar latitudes during winter/spring, or that the model fails to represent the dynamical response of the Southern Annular Mode (Marshall, 2003) with fidelity (Jones et al., 2021; 2022). Nevertheless, the similarity between the observed warm LST perturbations, and our physical modelling using state-of-the-art satellite retrievals and a state-of-the-art climate model leads us to conclude that the highly absorbing biomass burning aerosols from the 2019-2020 South East Australian wildfires caused the highest global mean LST anomaly since that caused by Pinatubo in 1991. It is likely that future climate change will increase the frequency and intensity of wildfire events (e.g. Walker et al., 2019; Jones et al., 2020) with implications for the frequency of stratospheric BBA events in the future.

3. Methods:

This study uses native night-time CALIOP and OMPS-LP retrievals to derive weekly average aerosol extinction vertical profiles and SAOD, for the period 29 December 2019 to 31 December 2020, at 10-degree latitude bands from 20°S to 70°S. This latitude range is selected to remove the impacts of contamination of the BBA SAOD by residual impacts from the eruption of Ulawun in Papua New Guinea in June 2019, which impacted latitudes north of 20°S and to remove data-sparse areas south of 70°S. Most BBA smoke produced by the Australian wildfires was observed to be contained within this latitude range (Hirsch and Koren, 2021). The long-term 'background' aerosol extinction vertical profiles and SAOD is calculated for the same date range, for both CALIOP and OMPS-LP, as weekly averages and at 10-degree latitude intervals, using data from June 2012 to December 2018. The long-term average excludes retrievals from 14 February to 31 December 2014 due to the eruption of Mt Kelut in Indonesia (Wunderman, 2014). Retrievals from 22 April 2015 to 11 July 2016 are also excluded as they appear anomalously high, because of the injection of SO₂ into the UTLS from explosive volcanic eruptions originating from South America (Calbuco) and Indonesia (e.g. Soputan, and an unidentified volcano on Gorontalo Island) and unusually active emissions from Ambrym and other volcanoes in Vanuatu (Carn et al., 2017). The perturbations in aerosol extinction coefficient and SAOD over the period January-December 2020 that are predominantly due to the Australian wildfires are calculated by subtracting the long-term background retrievals from the 2020 retrievals.

M1. CALIPSO/CALIOP Data and Quality Assurance: This study uses measurements of the aerosol extinction coefficient (km^{-1}) vertical profiles at 532nm, taken from the Version 4.20 (V4) CALIOP Level 2 data product, aboard the CALIPSO satellite. CALIOP is a dual-wavelength (532nm and 1064nm) polarization-sensitive lidar which provides high-resolution vertical profiles of aerosols and clouds. Although lidar retrievals are active rather than passive sensors, they are susceptible to solar contamination resulting in poorer performance during the daytime (Christian et al., 2020). Additionally, minimum detection thresholds for the aerosol extinction coefficient are estimated as 0.012 km^{-1} at night and 0.067 km^{-1} during the day (Rogers et al., 2014). Therefore, only aerosol extinction coefficient profile retrievals taken from CALIPSO night-time overpasses are used in this study.

Prior to analysis, quality control procedures, similar to those implemented by Campbell et al. (2012), are applied to the data. For a given vertical profile the extinction coefficient value is considered quality-assured if, for the corresponding entries i) Extinction_QC_Flag_532 is equal to 0, 1, 2, 16, or 18, ii) Extinction_Coefficient_Uncertainty_532 < 10, iii) Minimum_Laser_Energy ≥ 0.08 Joules. Extinction_QC_Flag_532 reports on the type of retrieval used when solving the extinction, aerosol extinction retrievals with a corresponding Extinction_QC_Flag_532 set to the above values are deemed to be stable and the solution falls within a range of acceptable values for the aerosol optical depth (AOD) and the magnitudes of extinction coefficient (Campbell et al., 2012). Extinction_Coefficient_Uncertainty values greater than 10 represent increasingly unrepresentative aerosol extinction coefficient values (Campbell et al., 2012). Since September 2016, CALIOP has been experiencing low-energy laser shots,

which primarily influence the quality of profile retrievals over the South Atlantic Anomaly (SAA) region. Hence, any profiles affected by 532nm laser energies less than 0.08 Joules are excluded from this study. In addition, entries with a fill value of -333 are removed and entries with a fill value of -9999 are set to zero.

M2. OMPS-LP Data and Quality Assurance: In addition to the CALIOP aerosol extinction data, we utilize retrievals of the vertical profile of the aerosol extinction coefficient (km^{-1}), taken from OMPS-LP Level 2 aerosol extinction coefficient daily product. The OMPS-LP views the Earth's limb, looking back along the orbital track, and measures the limb scattered radiation in the UV, visible, and near-infrared wavelengths to retrieve ozone density and aerosol extinction coefficient profiles (Johnson et al., 2020). This study uses non-cloud-filtered aerosol extinction coefficient profile retrievals, measured at 869nm along the centre slit (aligned with the orbital track) of the OMPS-LP. 869nm is chosen rather than wavelengths closer to the peak of the solar spectrum (e.g. 510nm), because there are clear performance issues at shorter wavelengths (Taha et al., 2021). The non-cloud-filtered retrievals are used since the stratospheric aerosol produced by the Australian Black Summer wildfires should be above any tropospheric cloud, and to avoid any misclassification of the optically thick aerosol plume as cloud.

As with the CALIOP data, quality control procedures are applied to the OMPS-LP data prior to analysis. The vertical profile of the aerosol extinction coefficient is considered quality assured if, for the corresponding entries i) ResidualFlag = 0, ii) SingleScatteringAngle $\leq 145^\circ$, iii) SwathLevelQualityFlags (a 16-bit integer) with bits 0, 1 and 7 = 0. A ResidualFlag of non-zero indicates that when retrieving the aerosol extinction profile, the cumulative residual error in the retrieval exceeds a threshold value (Johnson et al., 2020). Caution is advised when using LP extinction data with a scattering angle greater than 145° for wavelengths shorter than 675nm (Johnson et al., 2020). However, figure M1 shows that the average SAOD at 869nm becomes unreasonable when including the extinction retrievals with a scattering angle $>145^\circ$, thus these are screened out. To fill in the gaps in the dataset that result from screening out these retrievals (below 30°S , mainly during the southern hemispheric winter), a constant rate of decay of the SAOD within each latitude band is assumed (Figure M1). The rate of decay assumed ($k = 1/t$) is given by the e-folding time (t), calculated as the time it takes for the SAOD to reduce by a factor of $1/e$. Bits 0 and 1 of SwathLevelQualityFlags refer to the probability that the retrieval is affected by the SAA. If both bits are set to zero this indicates that the estimated SAA effects are $<5\%$ of the nominal maximum value at the satellite location (Johnson et al., 2020). Bit 7 of SwathLevelQualityFlags is the 'Non-Nominal Attitude' value which indicates changes to the spacecraft orientation, if this flag is set increased extinction profile noise is possible (Johnson et al., 2020). In addition, entries with a fill-value set to -999 are removed from the dataset.

Both CALIOP and OMPS-LP have known limitations in their aerosol extinction retrievals. As mentioned above, CALIOP has an estimated minimum detection threshold of 0.012 at night and a vertical resolution of 180m in the stratosphere, whereas OMPS-LP can reliably detect aerosol extinction coefficient values down to a minimum value of (Johnson et al., 2020) and has a vertical resolution of 1km. OMPS-LP suffers from loss of sensitivity of short wavelength radiances to aerosols, which is most pronounced

below ~17km and in the southern hemisphere (Johnson et al., 2020). In addition, the OMPS-LP extinction retrieval becomes unreliable in the presence of optically thick aerosol plumes (Johnson et al., 2020). The OMPS-LP retrieval issues are significant during the early stages of our study, during the fire emissions, as the aerosol was injected into the stratosphere at altitudes of ~16km (Kablick III et al., 2020). However, once the self-lofting of the aerosol occurs, and it ‘spreads out’ over the southern hemisphere, the increased stratospheric AOD is expected to be more detectable by OMPS-LP (Hirsch and Koren, 2021), but becomes undetectable by CALIOP due to its minimum detection threshold being considerably higher than OMPS-LP.

M3. Development of a Composite Stratospheric Aerosol Dataset

Due to the limitations above, the CALIOP and OMPS-LP datasets are combined into one interpolated dataset; this starts as solely CALIOP data in the initial weeks of the study, then shifts over to the OMPS-LP data. The extinction vertical profiles and SAOD values for each 10-degree latitude band are linearly interpolated in time only during the ‘crossover’ period. Linear interpolation is chosen to avoid the use of excessively complicated calculations to transition between the two datasets, whilst still producing a physically reasonable dataset. Prior to the interpolation, the CALIOP vertical profiles are converted from a 180m vertical grid to a 1km vertical grid, by calculating the weighted average aerosol extinction coefficient for each interval, to match the vertical resolution of the OMPS-LP profiles. This conversion for the CALIOP data preserves the observed SAOD. Additionally, the OMPS-LP aerosol extinction coefficient and SAOD retrievals are scaled from 869nm to 532nm, to ensure the interpolated values are at a single wavelength. We additionally calculate the average SAOD perturbation over the whole latitude range (20°S to 70°S). When doing so, each SAOD measurement is weighted by the cosine of its corresponding latitude to ensure the average SAOD is area weighted.

M4. The UKESM1 climate model and EasyAerosol

We used the United Kingdom Earth System Model version 1 (UKESM1) (Sellar et al., 2019) a fully coupled model with interactive tropospheric and stratospheric chemistry and aerosol. The control simulation for this study was a coupled run including the historical period (1850 - 2014) followed by a further 15 year period (2015 - 2029) where greenhouse gas concentrations, aerosol-chemistry emissions, and sea surface temperatures (SST) were maintained at 2014 levels to create a sample “present-day” climate. Thus, each year of the control after 2015 had the same forcing but different initial conditions and meteorological flow patterns. Yearly sections of the control from 2016 - 2025 (CNTL) were then used to form the basis of a 10-member ensemble with and without the COMP aerosol. All other model settings, including the SSTs were identical. Perturbation simulations ran for a full year from January - December and each followed a different meteorological evolution according to the initial conditions provided. The rationale for such an approach is that it samples different phases within the cycles of stratospheric natural variability such as the Quasi Biennial Oscillation, which are represented well by the UKESM1 model (e.g. Jones et al., 2021).

The COMP aerosol properties were included in the perturbation simulations using the model’s Easy Aerosol system. In this approach, aerosol optical properties are specified from an external data source

and provided directly to the model's radiation scheme. The Easy Aerosol method was used for UKESM1 in simulating stratospheric aerosol during the Coupled Model Intercomparison Project 6 (CMIP6) (Sellar et al., 2020). In the perturbation runs the scattering and absorption associated with the BBA were added on top of the background (historical mean) volcanic aerosol used in the control simulation. The BBA optical properties were set to match the aerosol extinction in the COMP data (described above) and were included as weekly, height resolved zonal-mean values, interpolated onto the UKESM1 grid. The wavelength dependence of the extinction, the single scattering albedo and the asymmetry parameters were derived from Mie scattering theory using size distributions retrieved from the AERONET station at Punta Arenas (Chile). The AERONET data was taken as the mean from all available retrievals during 26 - 30 January 2020 when the smoke originating from Australia was observed in the stratosphere above the Southern tip of South America and was dominating the AOD (0.24 - 0.28), relative to the background mean (0.056) taken from 2019-2021. The composition of the aerosol was assumed to be an homogeneous internal mixture with 5.4% black carbon and 94.6% organic carbon with mass densities of 1.9 and 1.35g cm⁻³, based on the measurements of Haywood et al. (2003). An updated BC refractive index of $1.85 + 0.71i$ was taken from Bond and Bergstrom (2006) and, when combined with an assumed non-absorbing OC refractive index of $1.50 + 0i$ and a volume-weighted averaging approach, yields an effective refractive index of $1.54 - 0.027i$. These above assumptions lead to a single scattering albedo of 0.86 at 550nm. This is slightly lower (more absorbing) than in Haywood et al. (2003), owing to the higher imaginary component of the refractive index and the broader size distribution provided by AERONET, but it is consistent with other more recent observations of aged smoke in the troposphere (Peers et al., 2019). Observations show the chemical composition, mixing state, and morphology of biomass burning aerosol to be highly variable in the troposphere as they depend on the combustion source and moisture content and the degree of smoldering and flaming combustion and hence the optical properties of biomass burning aerosols are extremely variable. In the upper troposphere and stratosphere, the uncertainty in the refractive indices, particularly in the imaginary part of the refractive index and single scattering albedo will be even larger owing to complexities associated with oxidation, bleaching, evaporation of volatile organic and inorganic components, the collapse of carbon chain structures, etc (e.g. Ohneiser et al., 2021). There is clear evidence emerging that stratospheric BBA smoke is more absorbing than tropospheric BBA smoke. For example, Haarig et al. (2018) and Hu et al (2019) derive a single scattering albedo at 532nm of 0.80 and 0.8-0.9 for aged Canadian boreal fires. Additionally, lidar observations of SE Australian smoke that reached South America during the episode that we study here (Ohneiser et al., 2020) displayed considerably higher lidar ratios (extinction/backscatter) which are indicative of more highly absorbing aerosol than their Canadian boreal BBA counter-parts.

M5. Stratospheric Temperature Anomaly Data

We consider observations of the LST anomaly in the lower stratosphere, based on measurements made by Microwave Sounding Units (MSU) channel 4 and Advanced Microwave Sounding Units (AMSU) channel 9 on polar-orbiting satellites. We use the TLS (Temperature Lower Stratosphere) single-channel data set of zonally averaged temperature anomalies, produced by Remote Sensing Systems

(RSS), which is sensitive to temperatures between altitudes of 12km to 27km. This dataset includes data from 13 different satellites, which are inter-calibrated before being merged (Mears and Wentz, 2009). The mean temperatures (T_b) used in this data set are given by:-

$$T_b = W_s T(0) + \int_0^{TOA} T(z) W(z) dz \quad (1)$$

where $T(z)$ is the atmospheric temperature at altitude z , $W(z)$ is a weighting function and W_s is the surface weight (Mears and Wentz, 2009). The RSS data set provides a continuous record of monthly temperature anomalies, from 1979 to the present day, averaged over several latitude bands (between 83°S and 83°N). The anomalies are computed by subtracting the mean monthly value, determined by averaging over a 1979-2019 reference period, from the average temperature for each month.

Declarations:

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References:

1. Abram, N.J., Henley, B.J., Gupta, A.S., Lippmann, T.J., Clarke, H., Dowdy, A.J., Sharples, J.J., Nolan, R.H., Zhang, T., Wooster, M.J. and Wurtzel, J.B., 2021. Connections of climate change and variability to large and extreme forest fires in southeast Australia. *Communications Earth & Environment*, 2(1), pp.1-17.
2. Angell, J.K., 1993. Comparison of stratospheric warming following Agung, El Chichon and Pinatubo volcanic eruptions. *Geophysical Research Letters*, 20(8), pp.715-718.
3. Angell, J.K., 1997. Stratospheric warming due to Agung, El Chichón, and Pinatubo taking into account the quasi-biennial oscillation. *Journal of Geophysical Research: Atmospheres*, 102(D8), pp.9479-9485.
4. Angell, J.K. and Korshover, J., 1984. Comparison of tropospheric temperatures following Agung and El Chichón volcanic eruptions. *Monthly weather review*, 112(7), pp.1457-1463.
5. Arblaster, J. M., Gillett, N. P., Calvo, N., Forster, P. M., Polvani, L. M., Son, S.-W., et al. (2014). Stratospheric ozone changes and climate. In Chapter 4 in Scientific assessment of ozone depletion: 2014, Global Ozone Research and Monitoring Project-Report No. 55 (Chap. 4, 61 pp.). Geneva, Switzerland: World Meteorological Organization.

6. Boer, M.M., de Dios, V.R. and Bradstock, R.A., 2020. Unprecedented burn area of Australian mega forest fires. *Nature Climate Change*, 10(3), pp.171-172.
7. Chen Z, Bhartia PK, Loughman R, Colarco P, DeLand M. Improvement of stratospheric aerosol extinction retrieval from OMPS/LP using a new aerosol model. Atmospheric measurement techniques. 2018 Dec 6;11(12),6495-509.
8. Christian, K., Wang, J., Ge, C., Peterson, D., Hyer, E., Yorks, J. and McGill, M., 2019. Radiative forcing and stratospheric warming of pyrocumulonimbus smoke aerosols: First modeling results with multisensor (EPIC, CALIPSO, and CATS) views from space. *Geophysical Research Letters*, 46(16), pp.10061-10071.
9. de Leeuw, J., Schmidt, A., Witham, C. S., Theys, N., Taylor, I. A., Grainger, R. G., Pope, R. J., Haywood, J., Osborne, M., and Kristiansen, N. I.: The 2019 Raikoke volcanic eruption – Part 1: Dispersion model simulations and satellite retrievals of volcanic sulfur dioxide, *Atmos. Chem. Phys.*, 21, 10851–10879, <https://doi.org/10.5194/acp-21-10851-2021>, 2021.
10. Dykema, J. D., D. W. Keith, and F. N. Keutsch, Improved aerosol radiative properties as a foundation for solar geoengineering risk assessment. *Geophys. Res. Lett.*, 43,7758-7766, doi:10.1002/2016GL069258, 2016.
11. Engel, A., Rigby, M., Burkholder, J.B., Fernandez, R.P, Froidevaux, L., Hall, B.D., Hossaini, R., Saito, T., Vollmer, M.K. and Yao, B., 2019. Update on ozone-depleting substances (ODSs) and other gases of interest to the Montreal Protocol, *Scientific assessment of ozone depletion: 2018* (2018): 1-1.
12. Ferraro, A.J., Collins, M. and Lambert, F.H., 2015. A hiatus in the stratosphere?. *Nature Climate Change*, 5(6), pp.497-498.
13. Flynn, L., Long, C., Wu, X., Evans, R., Beck, C.T., Petropavlovskikh, I., McConville, G., Yu, W., Zhang, Z., Niu, J. and Beach, E., 2014. Performance of the ozone mapping and profiler suite (OMPS) products. *Journal of Geophysical Research: Atmospheres*, 119(10), pp.6181-6195.
14. Fromm, M., Kablick III, G., Nedoluha, G., Carboni, E., Grainger, R., Campbell, J. and Lewis, J., 2014. Correcting the record of volcanic stratospheric aerosol impact: Nabro and Sarychev Peak. *Journal of Geophysical Research: Atmospheres*, 119(17), pp.10-343.
15. Fromm, M., Alfred, J., Hoppel, K., Hornstein, J., Bevilacqua, R., Shettle, E., & Stocks, B. (2000). Observations of boreal forest fire smoke in the stratosphere by POAM III, SAGE II, and lidar in 1998. *Geophysical Research Letters*, 27(9), 1407–1410. <https://doi.org/10.1029/1999GL011200>
16. Fromm, M., Bevilacqua, R., Servranckx, R., Rosen, J., Thayer, J. P., Herman, J., & Larko, D. (2005). Pyrocumulonimbus injection of smoke to the stratosphere: Observations and impact of a super blowup in northwestern Canada on 34 August 1998. *Journal of Geophysical Research*, 110, D08205. <https://doi.org/10.1029/2004JD005350>
17. Hansen, J., Lacis, A., Ruedy, R. and Sato, M., 1992. Potential climate impact of Mount Pinatubo eruption. *Geophysical Research Letters*, 19(2), pp.215-218.
18. Haarig, M., Ansmann, A., Baars, H., Jimenez, C., Veselovskii, I., Engelmann, R., and Althausen, D.: Depolarization and lidar ratios at 355, 532, and 1064 nm and microphysical properties of aged

- tropospheric and stratospheric Canadian wildfire smoke, *Atmos. Chem. Phys.*, 18, 11847–11861, <https://doi.org/10.5194/acp-18-11847-2018>, 2018.
19. Hirsch, E. and Koren, I., 2021. Record-breaking aerosol levels explained by smoke injection into the stratosphere. *Science*, 371(6535), pp.1269-1274.
20. Hu, Q., Goloub, P., Veselovskii, I., Bravo-Aranda, J.A., Popovici, I.E., Podvin, T., Haeffelin, M., Lopatin, A., Dubovik, O., Pietras, C. and Huang, X., 2019. Long-range-transported Canadian smoke plumes in the lower stratosphere over northern France. *Atmospheric Chemistry and Physics*, 19(2), pp.1173-1193.
21. Jones, A., Haywood, J. M., Jones, A. C., Tilmes, S., Kravitz, B., and Robock, A.: North Atlantic Oscillation response in GeoMIP experiments G6solar and G6sulfur: why detailed modelling is needed for understanding regional implications of solar radiation management, *Atmos. Chem. Phys.*, 21,1287–1304, <https://doi.org/10.5194/acp-21-1287-2021>, 2021.
22. Jones, A., J.M. Haywood, A.A. Scaife, O. Boucher, M. Henry, B. Kravitz, P. Nabat, U. Niemeier, R. Séférian, and D. Vioni, The impact of stratospheric aerosol intervention on the North Atlantic and Quasi-Biennial Oscillations in the Geoengineering Model Intercomparison Project (GeoMIP) G6sulfur experiment, *Atmos Chem Phys Discuss.*, acp-2021-898, 2022.
23. Jones, M.W., Smith, A., Betts, R., Canadell, J.G., Prentice, I.C. and Le Quéré, C., 2020. Climate change increases risk of wildfires. *ScienceBrief Review*, 116, p.117.
24. Kablick III, G.P., Allen, D.R., Fromm, M.D. and Nedoluha, G.E., 2020. Australian pyroCb smoke generates synoptic-scale stratospheric anticyclones. *Geophysical Research Letters*, 47(13), p.e2020GL088101.
25. Khaykin, S., Legras, B., Bucci, S., Sellitto, P., Isaksen, L., Tence, F., Bekki, S., Bourassa, A., Rieger, L., Zawada, D. and Jumelet, J., 2020. The 2019/20 Australian wildfires generated a persistent smoke-charged vortex rising up to 35 km altitude. *Communications Earth & Environment*, 1(1), pp.1-12.
26. Labitzke, K., Naujokat, B. and McCormick, M.P., 1983. Temperature effects on the stratosphere of the April 4, 1982 eruption of El Chichon, Mexico. *Geophysical Research Letters*, 10(1), pp.24-26.
27. Marshall, G.J., 2003. Trends in the Southern Annular Mode from observations and reanalyses. *Journal of climate*, 16(24), pp.4134-4143.
28. Maycock, A.C., Randel, W.J., Steiner, A.K., Karpechko, A.Y., Christy, J., Saunders, R., Thompson, D.W., Zou, C.Z., Chrysanthou, A., Luke Abraham, N. and Akiyoshi, H., 2018. Revisiting the mystery of recent stratospheric temperature trends. *Geophysical research letters*, 45(18), pp.9919-9933.
29. Ohneiser, K., Ansmann, A., Baars, H., Seifert, P., Barja, B., Jimenez, C., Radenz, M., Teisseire, A., Floutsi, A., Haarig, M., Foth, A., Chudnovsky, A., Engelmann, R., Zamorano, F., Bühl, J., and Wandinger, U.: Smoke of extreme Australian bushfires observed in the stratosphere over Punta Arenas, Chile, in January 2020: optical thickness, lidar ratios, and depolarization ratios at 355 and 532 nm, *Atmos. Chem. Phys.*, 20, 8003–8015, <https://doi.org/10.5194/acp-20-8003-2020>, 2020.
30. Ohneiser, K., Ansmann, A., Chudnovsky, A., Engelmann, R., Ritter, C., Veselovskii, I., Baars, H., Gebauer, H., Griesche, H., Radenz, M., Hofer, J., Althausen, D., Dahlke, S., and Maturilli, M.: The unexpected

- smoke layer in the High Arctic winter stratosphere during MOSAiC 2019–2020 , *Atmos. Chem. Phys.*, 21, 15783–15808, <https://doi.org/10.5194/acp-21-15783-2021>, 2021.
31. Peers, F., Francis, P., Fox, C., Abel, S. J., Szpek, K., Cotterell, M. I., Davies, N. W., Langridge, J. M., Meyer, K. G., Platnick, S. E., and Haywood, J. M.: Observation of absorbing aerosols above clouds over the south-east Atlantic Ocean from the geostationary satellite SEVIRI – Part 1: Method description and sensitivity, *Atmos. Chem. Phys.*, 19, 9595–9611, <https://doi.org/10.5194/acp-19-9595-2019>, 2019.
 32. Peterson, D. A., Campbell, J. R., Hyer, E. J., Fromm, M. D., Kablick, G. P., Cossuth, J. H., & DeLand, M. T. (2018). Wildfire-driven thunderstorms cause a volcano-like stratospheric injection of smoke. *npj Climate and Atmospheric Science*, 1(1), 30. <https://doi.org/10.1038/s41612-018-0039-3>
 33. Peterson, D.A., Fromm, M.D., McRae, R.H., Campbell, J.R., Hyer, E.J., Taha, G., Camacho, C.P., Kablick, G.P., Schmidt, C.C. and DeLand, M.T., 2021. Australia's Black Summer pyrocumulonimbus super outbreak reveals potential for increasingly extreme stratospheric smoke events. *npj Climate and Atmospheric Science*, 4(1), pp.1-16.
 34. Randel, W.J., Wu, F., Russell III, J.M., Waters, J.W. and Froidevaux, L., 1995. Ozone and temperature changes in the stratosphere following the eruption of Mount Pinatubo. *Journal of Geophysical Research: Atmospheres*, 100(D8), pp.16753-16764.
 35. Rao, J., Garfinkel, C.I., White, I.P. and Schwartz, C., 2020. The Southern Hemisphere minor sudden stratospheric warming in September 2019 and its predictions in S2S models. *Journal of Geophysical Research: Atmospheres*, 125(14), p.e2020JD032723.
 36. Redemann, J., et al.: An overview of the ORACLES (ObseRvations of Aerosols above CLouds and their intEractionS) project: aerosol-cloud-radiation interactions in the Southeast Atlantic basin, *Atmos. Chem. Phys.*, 21, 1507–1563, 2021, doi.org/10.5194/acp-21-1507-2021.
 37. Richter, J. H., Tilmes, S., Mills, M. J., Tribbia, J., Kravitz, B., MacMartin, D. G., ..., Jean-Francois, L. (2017). Stratospheric dynamical response and ozone feedbacks in the presence of SO₂ injections. *Journal of Geophysical Research: Atmospheres*, 122, 12,557–12,573. <https://doi.org/10.1002/2017JD026912>
 38. Rogers, R.R., Vaughan, M.A., Hostetler, C.A., Burton, S.P., Ferrare, R.A., Young, S.A., Hair, J.W., Obland, M.D., Harper, D.B., Cook, A.L. and Winker, D.M., 2014. Looking through the haze: evaluating the CALIPSO level 2 aerosol optical depth using airborne high spectral resolution lidar data. *Atmospheric Measurement Techniques*, 7(12), pp.4317-4340.
 39. Soden, B.J., Wetherald, R.T., Stenchikov, G.L. and Robock, A., 2002. Global cooling after the eruption of Mount Pinatubo: A test of climate feedback by water vapor. *Science*, 296(5568), pp.727-730.
 40. Steiner, A.K., Ladstädter, F., Randel, W.J., Maycock, A.C., Fu, Q., Claud, C., Gleisner, H., Haimberger, L., Ho, S.P., Keckhut, P. and Leblanc, T., 2020. Observed temperature changes in the troposphere and stratosphere from 1979 to 2018. *Journal of Climate*, 33(19), pp.8165-8194.
 41. Stocker, M., Ladstädter, F. and Steiner, A.K., 2021. Observing the climate impact of large wildfires on stratospheric temperature. *Scientific reports*, 11(1), pp.1-11.

42. Torres, O., P. K. Bhartia, G. Taha, H. Jethva, S. Das, P. Colarco, N. Krotkov, A. Omar, C. Ahn, Stratospheric injection of massive smoke plume from Canadian boreal fires in 2017 as seen by DSCOVR-EPIC, CALIOP, and OMPS-LP observations. *J. Geophys. Res. Atmos.* 125, e2020JD032579 (2020).
43. Walker, X.J., Baltzer, J.L., Cumming, S.G., Day, N.J., Ebert, C., Goetz, S., Johnstone, J.F., Potter, S., Rogers, B.M., Schuur, E.A. and Turetsky, M.R., 2019. Increasing wildfires threaten historic carbon sink of boreal forest soils. *Nature*, 572(7770), pp.520-523.
44. Winker, D.M., Vaughan, M.A., Omar, A., Hu, Y., Powell, K.A., Liu, Z., Hunt, W.H. and Young, S.A., 2009. Overview of the CALIPSO mission and CALIOP data processing algorithms. *Journal of Atmospheric and Oceanic Technology*, 26(11), pp.2310-2323.
45. Yamazaki, Y., Matthias, V., Miyoshi, Y., Stolle, C., Siddiqui, T., Kervalishvili, G., Laštovička, J., Kozubek, M., Ward, W., Themens, D.R. and Kristoffersen, S., 2020. September 2019 Antarctic sudden stratospheric warming: Quasi-6-day wave burst and ionospheric effects. *Geophysical Research Letters*, 47(1), p.e2019GL086577.
46. Yu, P., Davis, S.M., Toon, O.B., Portmann, R.W., Bardeen, C.G., Barnes, J.E., Telg, H., Maloney, C. and Rosenlof, K.H., 2021. Persistent Stratospheric Warming Due to 2019–2020 Australian Wildfire Smoke. *Geophysical Research Letters*, 48(7), p.e2021GL092609.
47. Yu, P., Toon, O. B., Bardeen, C. G., Zhu, Y., Rosenlof, K. H., Portmann, R. W., et al. (2019). Black carbon lofts wildfire smoke high into the stratosphere to form a persistent plume. *Science*, **365**, 587– 590. <https://doi.org/10.1126/science.aax1748>
48. Zuidema, P., J. Redemann, J.M. Haywood, R. Wood, S. Piketh, M. Hipondoka, P. Formenti, Smoke and Clouds above the Southeast Atlantic: Upcoming Field Campaigns Probe Absorbing Aerosol's Impact on Climate, Bulletin of the American Meteorological Society, DOI: <http://dx.doi.org/10.1175/BAMS-D-15-00082.1>, 2016.
49. Bond, Tami C., and Robert W. Bergstrom. "Light absorption by carbonaceous particles: An investigative review." *Aerosol science and technology* 40, no. 1 (2006): 27-67.
50. Campbell, J., Tackett, J., Reid, J., Zhang, J., Curtis, C., Hyer, E., Sessions, W., Westphal, D., Prospero, J., Welton, E., 2012. Evaluating nighttime CALIOP 0.532 μm aerosol optical depth and extinction coefficient retrievals. *Atmospheric Measurement Techniques* 5, 2143–2160.
51. Carn, S.A., Fioletov, V.E., McLinden, C.A., Li, C. and Krotkov, N.A., 2017. A decade of global volcanic SO₂ emissions measured from space. *Scientific reports*, 7(1), pp.1-12.
52. Christian, K., Yorks, J. and Das, S., 2020. Differences in the Evolution of Pyrocumulonimbus and Volcanic Stratospheric Plumes as Observed by CATS and CALIOP Space-Based Lidars. *Atmosphere*, 11(10), p.1035.
53. Haywood, J. M., Osborne, S. R., Francis, P. N., Keil, A., Formenti, P., Andreae, M. O., and Kaye, P. H. (2003), The mean physical and optical properties of regional haze dominated by biomass burning aerosol measured from the C-130 aircraft during SAFARI 2000, *J. Geophys. Res.*, 108, 8473, doi:10.1029/2002JD002226, D13.

54. Johnson, J., Taha, G., Loughman, R., Zhu, T., DeLand, M., 2020. README Document for the Suomi-NPP OMPS LP L2 AER Daily Product.
55. Mears, C.A. and Wentz, F.J., 2009. Construction of the RSS V3. 2 lower-tropospheric temperature dataset from the MSU and AMSU microwave sounders. *Journal of Atmospheric and Oceanic Technology*, 26(8), pp.1493-1509.
56. Sellar, A. A., Jones, C. G., Mulcahy, J.P., Tang, Y., Yool, A., Wiltshire, A., et al. (2019). UKESM1: Description and evaluation of the U.K. Earth System Model. *Journal of Advances in Modeling Earth Systems*, 11, 4513-4558, <https://doi.org/10.1029/2019MS001739>.
57. Sellar, A. A., Walton, J., Jones, C. G., Wood, R., Abraham, N. L., Andrejczuk, M., et al. (2020). Implementation of U.K. Earth system models for CMIP6. *Journal of Advances in Modeling Earth Systems*, 12, e2019MS001946. <https://doi.org/10.1029/2019MS001946>
58. Taha, G., Loughman, R., Zhu, T., Thomason, L., Kar, J., Rieger, L. and Bourassa, A., 2021. OMPS LP Version 2.0 multi-wavelength aerosol extinction coefficient retrieval algorithm. *Atmospheric Measurement Techniques*, 14(2), pp.1015-1036.
59. Wunderman, R., 2014. Global Volcanism Program, 2014. Report on Kelut (Indonesia). *Bulletin of the Global Volcanism Network*, 39(02).

Figures

Figure 1

Examples of lidar observations of i) first column) the vertical distribution of the 532nm total attenuated backscatter and the tropopause height (black line), ii) middle column) the aerosol sub-type identified by the CALIOP sensor. The third column represents the lidar footprint of the corresponding observations. The position of the Punta Arenas AERONET site is represented on the bottom right-hand plot by the blue dot in the extreme south of Chile. Notable aerosol sub-types in the stratosphere include type 6 - smoke, and types 9 - volcanic ash and 10 – sulfate/other.

Figure 2

Weekly average perturbation in the SAOD (532nm) over latitudes 20 to 70°S, as observed by CALIOP and OMPS-LP following the Australian Black Summer wildfires. The OMPS-LP retrievals are scaled from 869nm to 532nm assuming an appropriate Ångström exponent. The purple dashed line is a fit that linearly interpolates between the peaks in the CALIOP and OMPS-LP retrievals, illustrating the method used to derive the composite SAOD (COMP) dataset.

Figure 3

Perturbations in aerosol extinction coefficient due to the Australian Black Summer Fires, as a function of latitude and altitude derived by the COMP interpolated dataset. Each image shows the weekly mean distribution for the 10-degree latitude intervals from 20°S to 70°S, and 1km height intervals from 0km to 35km. The black line shows the average tropopause height from the UKESM1 model climatology.

Figure 4

Monthly mean modelled perturbations to atmospheric temperature (K) due to the smoke aerosol forcing, with the average monthly aerosol absorption (km^{-1}) overlaid. The stippled points show the points at which the experiments were significantly different from the controls at a 5% significance level (calculated by a Welch's t-test).

Figure 5

Monthly-mean lower stratospheric temperature (LST) anomalies provided by MSU/AMSU data (a), and the mean of the 10-member ensemble of UKESM1 simulations (b). Temperature anomalies are calculated relative to a 1979-2019 reference period, and averaged over latitudes 83°S to 83°N. The difference in the LST anomalies relative to November 2019 are shown in c). In addition, the difference in the LST anomalies given by the mean of the 10 control runs with the 95% confidence intervals for each month of 2020, assuming a Student's t-distribution, are shown in (c).

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