3. D5.2: Report on the global radiative forcing of selected stratospheric smoke injections

Introduction

Smoke is largely composed of organic and black carbon, numerous reactive gases, and other aerosol precursors. Black carbon (BC) is of particular interest as it is the strongest absorber of shortwave light. Absorption by BC heats the plume causing shelf-lofting to higher altitudes, which prolongs the smoke lifetime and amplifies radiative and chemical perturbations. The global and regional radiative effects and feedbacks associated with stratospheric smoke are uncertain, partly because smoke ageing in the stratosphere is not well constrained. Apart from radiative perturbations, smoke may also accelerate ozone destruction via a) heterogeneous chlorine chemistry, b) moistened stratosphere and water vapor photolysis, c) chlorine activation on polar stratospheric clouds (PSCs), and d) changes in circulation. These mechanisms are known through studies of volcanic aerosols, but their chemical reactivity might differ for smoke, given the different nature of smoke aerosols. Smoke, for example, could develop glassy surfaces in contrast to liquid-coated sulphates. Understanding smoke-ozone mechanisms is imperative, because international efforts to regulate ozone recovery might be at risk if stratospheric smoke is a potent ozone-depleting agent. Substantial ozone recovery is expected by 2050, assuming global compliance with the Montreal Protocol, but more intensive and/or frequent smoke injections in the future could slow or disrupt ozone recovery and enhance UV radiation levels for years.

Wild fires frequently emit smoke in the upper troposphere and sometimes in the stratosphere. This events have the potential to influence radiative balance in remote locations far away from the source. The North American and Siberian fires can yield very strong contributions over Europe. Pronounced Canadian events have been frequently observed in the troposphere. Also in the stratosphere, dense Canadian smoke plumes have been observed with growing frequency (Fromm et al., 2022). One spectacular event was that of the wild fires in British Columbia (BC) starting in August 2017. the smoke gradually rose to more than 20 km above the northern Alps. Ansmann et al. (2018) determined an extreme aerosol optical thickness (AOT) close to 1.0 at 532 nm in this layer that crossed central Europe at a height of 3 to 17 km on 21 to 22 August 2017. They concluded from measurements at three stations were up to 20 times higher than the maximum extinction coefficients reached after the Pinatubo eruption in June 1991

The largest known stratospheric smoke injection was associated with the fierce Australian wildfires in the "Black Summer" of 2019/2020 (Ohneiser et al., 2020). Numerous pyroCbs injected over 1 million tons of smoke particles into the stratosphere, reaching altitudes up to 35 kilometers. The mass and reach of this aerosol injection exceeded all volcanic aerosol injections over the last 30 years. Satellite- and ground-based measurements subsequently detected self-lofting, significant stratospheric warming, and a considerable reduction in mid-latitude ozone that lasted several months. During November-December 2020, the Antarctic ozone hole reached a decadal high in magnitude and persistence, along with record-low polar temperatures and a strong polar vortex. The magnitude of the record-high ozone depletion event in 2020 corresponds to a ~10-year delay in ozone recovery. It remains uncertain, however, if this event was caused by the Australian wildfires, but here we test the idea that smoke enhanced PSC chlorine activation, strengthened the polar vortex, and accelerated Antarctic ozone loss.

During "Black Summer", mainly between 29 December 2019 and 4 January 2020, several intense pyroCb events transported between 0.3 and 2 Tg of smoke particles up to 14–16 km height (Sellitto et al., 2022). The resulting smoke layer extended across the southern midlatitudes and high latitudes and could be detected in the stratosphere for as long as 2 years after the event.

Direct radiative forcing in the literature

The "direct radiative effect" refers to the change in the radiation budget of the Earth due to the scattering and absorption of incident solar radiation. This absorption of radiation results in heating rate changes within the aerosol-containing atmospheric layers. In turn, this heating causes rapid atmospheric adjustments to the instantaneous aerosol forcing and has the potential to alter atmospheric dynamics and circulation.

The Australian black summer wild fire event had significant effects on the radiation budget. Its instantaneous positive radiative forcing in the Southern Hemisphere was estimated to be as high as +0.5 W m−2 (Heinold et al., 2022). The actual radiative effect by the smoke aerosol would however be moderated by longwave adjustments in the stratosphere (Yu et al., 2019). Besides the above-mentioned value, a variety of other results for radiative forcing (RF) by Australian smoke can be found in the current literature. Reported values range from around 0.8 W m−2 to −1.0 W m−2 (Sellitto et al., 2022) . It has been argued that the large spread can be attributed to uncertainties in the optical properties of the smoke, i.e., absorptivity and backscattered fraction (Senf et al., 2023).

Simulations with EMAC

We carry out sensitivity simulations to examine the sensitivity of the stratospheric aerosol loading to injection height of the smoke (Table 1). The model is running with nudged meteorology from ERA5 till 28 December 2019 and freely thereafter till the end of 2020. We emit 0.9 Tg of smoke composed by 97.5% organic carbon and 25 % Black Carbon. The particles are emitted in the insoluble Aitken mode. These simulations are also described in D5.1.

Figure 1 shows perturbations the zonal mean extension coefficients from Dec-2019 till Aug-2020 in the stratosphere caused by the Black summer event. Our simulations show that smoke particles spread through the entire SH stratosphere within about 2 months. In the lower stratosphere (<16 km), transport was polewards reaching 80°S in January of 2020 but the main portion of the mass reaches one month after. This indicative of a fast transport from the shallow branch of Brewer-Dobson circulation. Portions of the smoke that were lofted higher (up to 25 km) moved equatorward and even cross the equator. This is like the observed response in the OMPS-LP satellite observations.

The higher the smoke reached, the longer its residence time and the greater the mixing throughout the hemisphere due to wind shear and dispersion(Yu et al., 2021). Observations from Mauna Loa Observatory lidar show that the aerosol backscatter ratio is a factor of 3–5 larger than model simulations (Senf et al., 2023). The large discrepancy is likely attributed to the Raikoke and Ulawun volcanic injections, which are not included in the model results presented in this study.

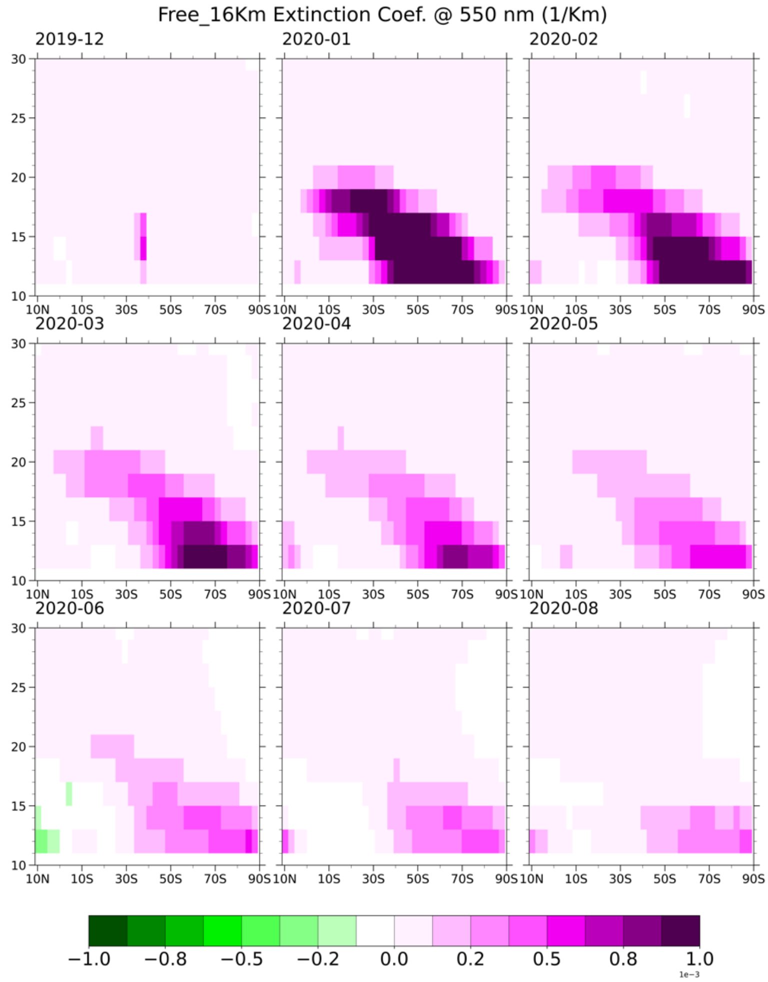

Figure 1 Zonal mean extinction coefficients anomalies from the smoke emission at 16 Km height.

Black carbon absorbs sun light and the heating lofts the smoke plume and surrounding air parcels. The amount of heating, and therefore the rate of plume rise is determined by the amount of BC within the smoke. However, the total optical depth is dominated by the amount of OC in the plume. The sudden increase in OC/BC burden due to the Australian fire outbreak led to a significant rise in absorption of shortwave radiation in the middle atmosphere (Figure 2) that mainly localized over the southern Pacific Ocean during January 2020 (not shown) with large-scale average values of shortwave radiation flux convergence larger than 5 W m−2.

Atmospheric mixing and transport led to a more equal redistribution of stratospheric smoke aerosol in the subsequent months (Figure 1). Simulations with nudged meteorology indicate that significant amounts of smoke have been transported polewards with the implications that the bright Antarctic surface may have been darkened by stratospheric smoke when viewed from TOA (Senf et al., 2023).

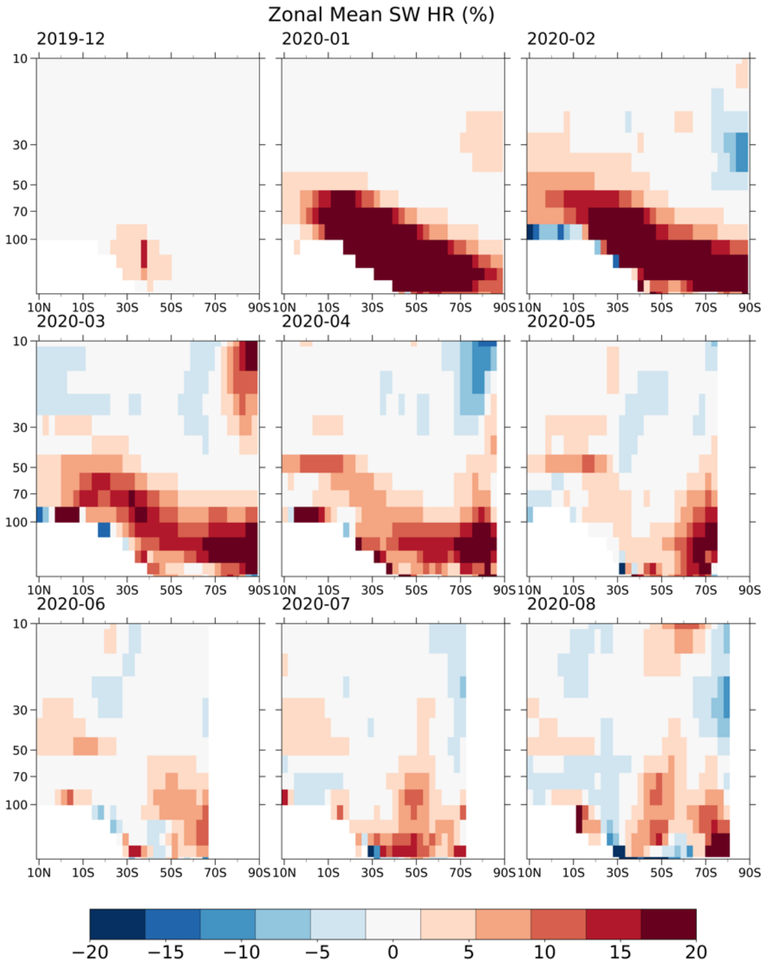

Figure 2 Percentage changes of the shortwave heating rates (%) from the smoke emission at 16 Km height.

The average longwave forcing of the middle atmosphere (see Figure 3) appears to be weaker in amplitude than the shortwave forcing. The maximum amplitude is reached in February 2020 and is characterized with a horse-show pattern of positive atop negative anomalies. It is not straight forward to interpret the signal and might be related to infrared emission from the water vapor but further investigation is required. The high latitude negative LW heating anomalies should be interpreted as dynamical adjustments to the smoke forcing realized by changes in the global circulation pattern and thus need to be interpreted as global adjustments to stratospheric smoke–radiation interactions.

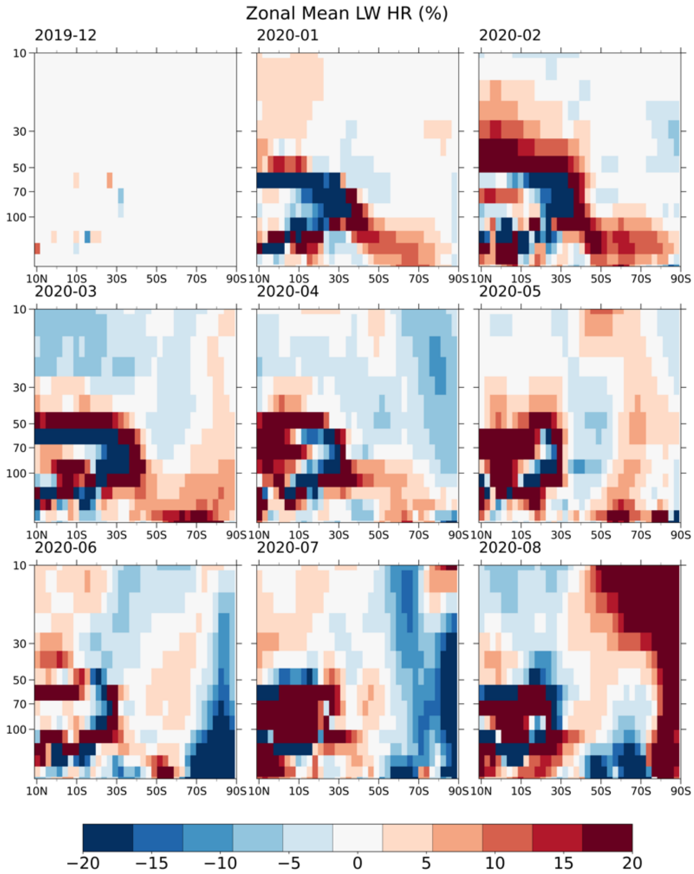

Figure 3 Percentage changes of the longwave heating rates (%) from a smoke emission at 16 Km height.

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