2. D4.2: Report on the radiative properties of stratospheric smoke, along with a sensitivity analysis due to the uncertainties of the optical properties of the particles used in the calculations.

Introduction

The 2019-2020 Australian bushfires, often referred to as the "Black Summer," were a series of devastating fires that ravaged vast areas of Australia. These fires were unprecedented in their scale, duration, and intensity, causing widespread destruction and significant atmospheric impacts. One of the most profound atmospheric consequences was the injection of massive quantities of smoke and aerosols into the stratosphere. This report examines the radiative properties of the stratospheric smoke resulting from these fires and explores the sensitivity of radiative forcing estimates to uncertainties in the optical properties of the particles.

The "Black Summer" fires released approximately 0.9 teragrams (Tg) of smoke into the stratosphere, driven by intense heat and pyroconvective events. These pyrocumulonimbus (pyroCb) clouds formed due to the extreme temperatures, facilitating the vertical transport of smoke to altitudes exceeding 20 kilometers. The smoke particles consisted of black carbon (BC), organic carbon, and other aerosols, which have complex interactions with solar radiation and influence the Earth's radiative balance.

Stratospheric aerosols, especially those containing black carbon, can significantly alter the radiative properties of the atmosphere. These aerosols scatter and absorb sunlight, affecting both the top-of-atmosphere (TOA) radiative forcing and the surface radiative forcing. The distribution and persistence of these aerosols in the stratosphere lead to prolonged climatic effects, including surface cooling and stratospheric warming. Understanding the radiative forcing and balance perturbations caused by these aerosols is crucial for assessing their impact on climate and atmospheric chemistry.

Radiative Properties of Stratospheric Smoke

Injection and Composition

The Australian bushfires resulted in an unprecedented injection of smoke into the stratosphere. Pyrocumulonimbus clouds played a critical role in this process, transporting smoke and aerosols to high altitudes. According to Yu et al. (2021), the smoke from these fires was lofted to altitudes of up to 20 kilometers, where it remained for several months due to the stable stratospheric conditions. The smoke particles were primarily composed of black carbon (BC), organic carbon, and other aerosols, which influenced their radiative properties.

Radiative Forcing Estimates

Top-of-Atmosphere Radiative Forcing

Sellitto et al. (2022) estimated that the global mean clear-sky top-of-atmosphere (TOA) radiative forcing of the stratospheric smoke was around -0.03 W m^{-2}, indicating a slight net cooling effect. However, regional variations, particularly in the Southern Hemisphere, showed more significant effects. The TOA radiative forcing ranged from small positive values to as much as -2.0 W m^{-2}, depending on the underlying surface reflectivity and aerosol distribution.

Surface Radiative Forcing

The surface radiative forcing was more pronounced, with an average global value of -0.32 W m^{-2} for the year 2020. In the Southern Hemisphere, surface radiative forcing reached values up to -4.5 W m^{-2}. This negative forcing was primarily due to the absorption and scattering of sunlight by the aerosols, reducing the amount of solar radiation reaching the Earth's surface. This led to surface cooling, especially over cloud-free oceanic areas (Hirsch & Koren, 2021).

Perturbations in Radiative Balance

Stratospheric Aerosol Optical Depth

The smoke injection caused a significant increase in stratospheric aerosol optical depth (SAOD), comparable to levels observed after moderate volcanic eruptions. This enhanced SAOD reduced incoming solar radiation, contributing to surface cooling in the Southern Hemisphere. The persistence of stratospheric aerosols for several months extended the duration of these radiative perturbations (Khaykin et al., 2022). The heights which the enhanced aerosol burden was injected into the stratosphere as observed from satellite measurements is presented in **Figure 1**, depicting the Global Space- based Stratospheric Aerosol Climatology (GloSSAC V2.21; Kovilakam et al., 2020) 25°-40° S average extinction coefficient at 525 nm for the year 2020. The GloSSAC dataset merges measurements by the Stratospheric Aerosol and Gas Experiment (SAGE) series of instruments through mid-2005 and on the Optical Spectrograph and InfraRed Imager System (OSIRIS) and the Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation (CALIPSO) data thereafter. Equally, **Figure 2** shows the European Space Agency (ESA) Climate data REcord of STratospheric Aerosols (CREST) aerosol extinction at 750 nm highlighting the differences in the both the height and the temporal evolution of the stratospheric aerosol perturbation due the Australian wildfires of 2019-2020 between the two observational datasets. It should be noted that the ESA CREST dataset merges measurements by six limb and occultation satellite instruments: SAGE II on ERBS, GOMOS and SCIAMACHY on Envisat, OSIRIS on Odin, OMPS on Suomi-NPP, and SAGE III on International Space Station.

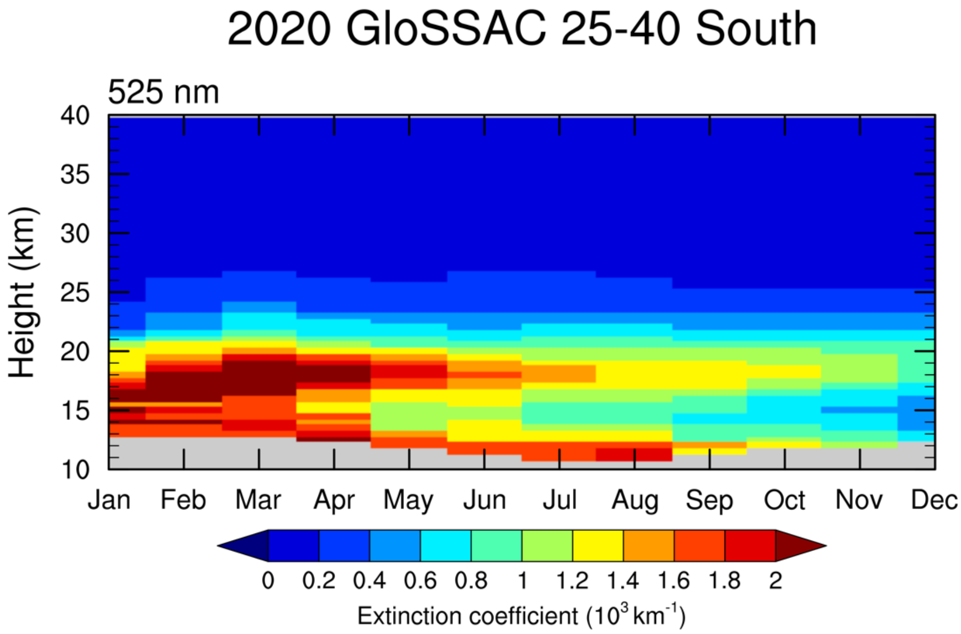

Figure 1. Altitude-resolved GloSSAC extinction coefficient at 525nm averaged between 25°-40° S for the year 2020.

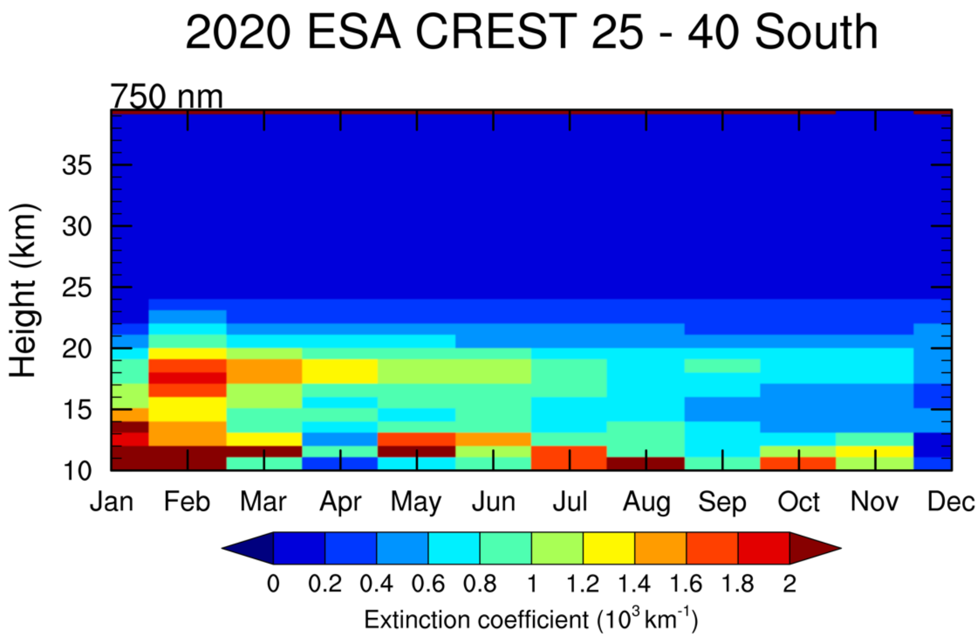

Figure 2. Altitude-resolved ESA CREST extinction coefficient at 750nm averaged between 25°-40° S for the year 2020.

Stratospheric Warming

The presence of black carbon in the stratosphere induced a warming effect due to solar absorption. Yu et al. (2021) reported a stratospheric temperature increase of approximately 1-2 K in the Southern Hemisphere midlatitudes, lasting for over six months. This warming altered stratospheric dynamics and potentially affected the ozone layer through chemical interactions with the smoke particles.

Sensitivity Analysis

Uncertainties in Optical Properties

The radiative forcing calculations depend heavily on the optical properties of the stratospheric smoke particles, which include parameters such as single scattering albedo, asymmetry factor, and particle size distribution. These properties determine how particles absorb and scatter sunlight.

Single Scattering Albedo

The single scattering albedo (SSA) of the particles, which is the ratio of scattering to total extinction (scattering + absorption), varies significantly. The SSA values for stratospheric smoke from the Australian fires ranged from 0.25 to 0.7, indicating a considerable uncertainty in the absorption properties of the particles (Hirsch & Koren, 2021). Higher SSA values suggest less absorption and more scattering, leading to a more pronounced cooling effect at the surface and a less significant warming in the stratosphere.

Asymmetry Factor

The asymmetry factor, which describes the angular distribution of scattered light, also influences the radiative forcing. Variations in this factor can alter the estimated cooling or warming effects. Sellitto et al. (2022) highlighted the sensitivity of radiative forcing estimates to changes in the asymmetry factor, emphasizing the need for precise measurements to reduce uncertainties.

Impact of Uncertainties on Radiative Forcing

The uncertainties in optical properties translate to significant variations in radiative forcing estimates. For example, the range of SSA values could result in a surface radiative forcing variation of up to ±0.2 W m^{-2} globally. Similarly, regional estimates could vary more widely due to differences in underlying surface albedo and aerosol concentrations. These uncertainties underscore the importance of accurate characterization of aerosol properties for reliable climate impact assessments.

Summary

The 2019-2020 Australian bushfires had a substantial impact on the Earth's radiative balance through the emission of stratospheric smoke. The radiative forcing effects included significant surface cooling and stratospheric warming, with complex regional variations. The sensitivity analysis reveals that uncertainties in the optical properties of the smoke particles play a crucial role in determining the extent of these radiative effects. Accurate measurements and improved modeling are essential for reducing these uncertainties and enhancing our understanding of the climatic implications of such extreme wildfire events.

References

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