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Biomass Burning Uncertainties: Emissions, Chemistry, and Physics

Biomass Burning in Australia: No Evidence for Carbonyl Sulfide (OCS) Enhancement in Fire Plumes From In-Situ Measurements During SouthTRAC

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Key Points:

- Observations of biomass burning from Australian bushfires 2019 in the upper troposphere and lower stratosphere over South America
- Determination of biomass burning related enhancement of trace species using tracer-tracer correlations and emission factors
- No evidence for OCS enhancement in the biomass burning plume

Supporting Information:

Supporting Information may be found in the online version of this article.

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Abstract

Determining the atmospheric abundance and the emission sources of carbonyl sulfide (OCS) plays a crucial role for the sulfur budget in the atmosphere. In addition to its main anthropogenic and biogenic sources, biomass burning is assumed to be an essential, but not well constrained source of OCS. From November 2019 onward extensive bushfires along the eastern coast of Australia released huge amounts of trace species into the atmosphere; during one flight of the SouthTRAC campaign air masses were observed carrying signatures of these fires along the southern coast of South America. An analysis of the composition of air masses inside and outside the plume revealed distinct differences in the trace species abundances. Specifically, our results indicate that OCS shows no enhancement in its atmospheric mixing ratio due to the Australian fires and thus highlights the varying emission strength of OCS for different types of biomass burning.

Plain Language Summary

Carbonyl sulfide (OCS) is a molecule that occurs naturally in the atmosphere, but in very small amounts. It is a source of sulfur dioxide and acts as a precursor to stratospheric sulfate aerosol. It further can be used to quantify biogenic carbon dioxide uptake. Therefore, it is also important to know the sources of OCS in the atmosphere. Until now, it is assumed that biomass burning is an important source of OCS for the atmosphere. We report on a case study from 12 November 2019 during the SouthTRAC aircraft campaign, where we encountered a fire plume in the stratosphere from bushfires in Australia. Compared to the natural background of carbon monoxide (CO) in the lower stratosphere (below 70 ppbv), we observed mixing ratios of CO up to 400 ppbv. In contrast, OCS showed no enhancement compared to the natural background in these fire plumes. This concludes that OCS emissions from biomass burning are quite variable and possibly strongly depend on the type of burnt vegetation.

1. Introduction

Carbonyl sulfide (abbreviated either OCS or COS) plays a crucial role in the global sulfur cycle as the most abundant sulfur-containing trace gas in the atmosphere. With its long tropospheric lifetime of 1.5–3.0 years (Montzka et al., 2007), OCS also occurs in the stratosphere where it is chemically converted to SO_2 and further sulfate aerosols contributing to the Junge sulfate aerosol layer and exerting a small cooling effect on climate (Brühl et al., 2012; Gurganus et al., 2025; Kremser et al., 2016). Given the high mean lifetime of 47–70 years in the stratosphere and the absence of stratospheric sources, OCS can be used as a tracer for dynamic processes in the stratosphere (Barkley et al., 2008; Karu et al., 2023; Krysztofiak et al., 2015). Furthermore, the concentration of OCS in the atmosphere can be used as a proxy for the photosynthetic uptake of CO_2 by plants (Campbell et al., 2008; Montzka et al., 2007), aiding in the improvement of climate models and their prediction of CO_2 fluxes (Campbell et al., 2017; Lai et al., 2024).

Biomass burning has an essential impact on the atmospheric composition as a substantial source of pollution and aerosols (Andreae, 2019; Crutzen et al., 1979; Wiedinmyer et al., 2011). On the one hand, biomass burning releases many species directly into the atmosphere; trace species such as carbon monoxide (CO), carbon dioxide

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(CO_2) or nitrogen oxides as NO_x or NO_y are well enhanced downwind of the emission source. On the other hand, chemical reactions within the fire plume and downwind the sources substantially alter the atmospheric composition with the potential for enhancement or depletion. For example, there may occur ozone (O_3) production or depletion processes in reaction with the air masses from the fire plume (Bernath et al., 2022; Jaffe & Wigder, 2012).

Biomass burning is assumed to be an essential source of OCS (Campbell et al., 2015; Crutzen et al., 1979). Besides, OCS is primarily emitted from oceans (more than 50%) and from anthropogenic sources, mainly industrial processes and fossil fuel combustion (about 15%–35%). The main sinks are the uptake of OCS by vegetation and soil, and its oxidation by OH radicals (Kettle et al., 2002; Watts, 2000). At the current state of knowledge, the distribution of OCS emission sources and sinks in the atmosphere is still not completely understood. According to a gap between the expected and measured OCS concentrations, a missing source for OCS is assumed (Berry et al., 2013). While biomass burning has been hypothesized as a major contributor to the missing OCS, recent studies have cast doubt on its significance (Hattori et al., 2020; Stinecipher et al., 2019).

Many studies of OCS emissions from biomass burning are based on laboratory studies (Yokelson et al., 1997), satellite measurements (Glatthor et al., 2017) or observations near to the fire - either at the ground or by aircraft (Nguyen et al., 1995). Blake et al. (2004, 2008) identified air masses by aircraft originating from fire plumes in the mid-latitudes that were a few days old by which OCS mixing ratios were slightly enhanced. However, the identification of the fire plume and the detection of OCS were spatially and temporally limited by the multi-minute sampling interval.

In this paper, we analyze whether Australian bushfires in early November 2019 (Deb et al., 2020) potentially contributed to OCS enhancements. We additionally investigate their influence on the upper troposphere/lower stratosphere composition, as such perturbations have been observed for the Australian bushfire season 2019/2020 (Santee et al., 2022). To estimate the potential OCS emissions, we utilize trace gas observations from flight 25 of the SouthTRAC (Southern Hemisphere - Transport Composition Dynamics) campaign (Johansson et al., 2022; Rapp et al., 2021; German Aerospace Center (DLR), 2019), hereafter referred to as ST25, which was conducted over the Drake Passage on 12 November 2019. Compared to previous work (e.g., Kloss et al., 2021), we evaluate the vertical location of the fire plume and compare key trace gas emissions against literature-derived values.

2. Data and Methods: In-Situ Measurements and Tools for Plume Analysis

For our OCS investigations during the Australian bushfires, we analyze observations from ST25. The SouthTRAC campaign was a measurement campaign in 2019 with the German research aircraft HALO (High Altitude and Long Range Research) starting at Tierra del Fuego (Río Grande, Argentina). Our analysis focuses on the high-precision data obtained from the UMAQS-instrument (University of Mainz Airborne Quantum Cascade Laser Spectrometer; Müller et al., 2015) which is based on direct absorption spectroscopy with quantum cascade lasers in the mid-infrared spectral range. With this setup, we measure the mixing ratios for the trace gases CO, CO_2, N_2O and OCS. The instrument is calibrated in situ with two different working standards of compressed ambient air, which are compared to NOAA (National Oceanic and Atmospheric Administration) standards before and after the mission. The measurement total uncertainties (1σ, 1 Hz data) for UMAQS-derived mixing ratios were CO: 3.1 ppbv, CO_2: 0.5 ppmv, N_2O: 0.48 ppbv, and OCS: 27.5 pptv. Furthermore, we use ozone from the FAIRO instrument (ozone detection via dry chemiluminescence; Zahn et al., 2012) and NO/NO_y-data from the AENEAS instrument (nitrogen oxide measurement using chemiluminescence with a gold converter; Ziereis et al., 2000). Data from all instruments were first averaged to 10-s resolution and then smoothed with a 60-s box car filter to suppress high-frequency noise while preserving spatial features relevant to plume identification. To contextualize the aircraft measurements, we employ ERA5 reanalysis data (Hersbach et al., 2020) for meteorological context and the trajectory model LAGRANTO (Sprenger & Wernli, 2015) driven by ERA5 reanalysis winds to identify the recent transport pathways of the observed air masses.

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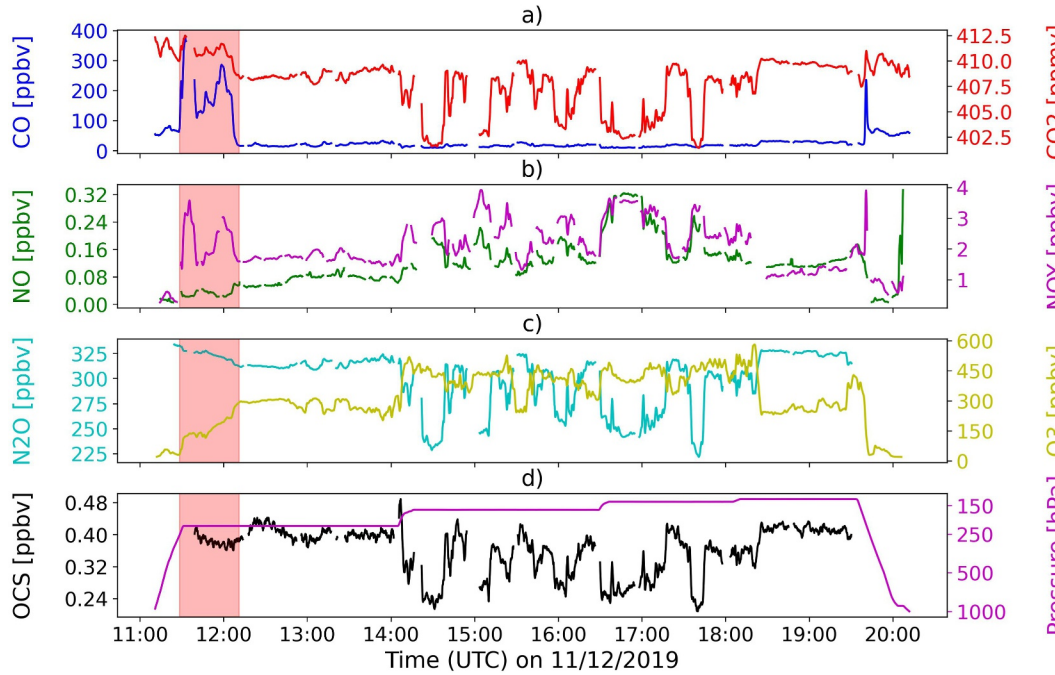

Figure 1. Time series of mixing ratios of CO, CO_2, NO, NO_y, N_2O, O_3 and OCS, and pressure during ST25 (53.3°–70.3°S). The red shaded area indicates the identified biomass burning signatures shortly after the ascent.

3. Results and Discussion

3.1. Detection of Biomass Burning Signatures During ST25

The primary objective of the flight was to characterize ozone depletion in a filament originating in the polar vortex, as was the case between 14:30 and 17:30 UTC, as is evident by the positive correlation of N_2O, CO_2 and OCS (see Figure 1). This finding highlights the accuracy of OCS measurements obtained during ST25 as the species are expected to correlate in the stratosphere due to their stratospheric sinks. Furthermore, two additional notable features can be identified: Shortly after the initial ascent to the first leg on a constant pressure level at ∼216 hPa, substantial enhancements of CO are evident between 11:30–12 UTC. Similarly, at the start of the descent around 19:40 UTC enhanced CO values have been encountered again. Notably, these CO mixing ratios of up to 400 ppbv over the Drake Passage along the southern coast of South America represent the maximum CO values during the entire SouthTRAC campaign which covered a period of over two months and the region between central Europe and Antarctica. The two features are distinguishable from the stratospheric background mixing ratios of approximately 10–35 ppbv. Additionally, enhancements of other species, such as CO_2 and NO_y, were observed to coincide with the CO enhancement. The presence of these enhancements suggests that the air masses originate from a biomass burning plume, since CO, CO_2 and NO_y are associated with combustion emissions.

The increase in CO can be clearly identified as an anomaly in the correlations with N_2O and O_3 (Figures 2d and 2ed). Conversely, other measured species such as N_2O, O_3, OCS or NO exhibited no strong enhancements during the observed biomass burning signatures (see also discussion below). The absence of a discernible peak for NO (Figure 1), akin to that observed in NO_y, signifies that NO, as a tracer for fresh plumes, has already undergone reaction to form alternative nitrogen compounds. Given the rapid interconversion between NO and NO_2, the atmospheric lifetime of NO is effectively governed by that of NO_x, which typically ranges from several hours to days (Akagi et al., 2012; Alvarado et al., 2010; Badr & Probert, 1993). This suggests that the assumed fire plume has at least an age on the order of several hours, rather than being freshly emitted. Furthermore, it is evident that O_3 and OCS exhibit lower mixing ratios in the fire plume after ascent than at the same pressure levels for the remainder of the flight. No enhancement of OCS is visible in the assumed fire plume region in the vertical profile

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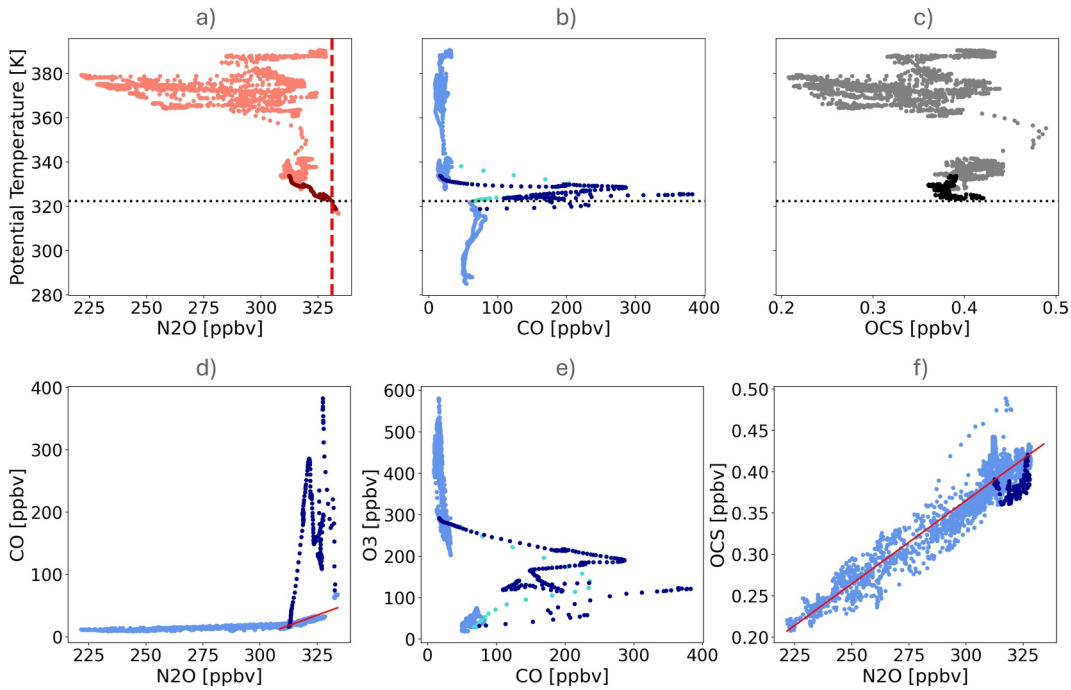

Figure 2. Vertical profiles as a function of potential temperature (a, b, c) and correlation plots of different species (d, e, f) for ST25. Biomass burning signatures are highlighted in dark colors, bright colors denote the rest of the flight. Cyan colors for CO in (b, e) indicate the second plume encounter during descent (no OCS/N_2O data available). The black dotted line marks the tropopause identified from N_2O threshold of 331.1 ppbv (red dashed line, a). The red line in (d, f) shows stratospheric background to detected plume.

or in correlation with N_2O (Figures 2c and 2f). A more detailed analysis of O_3 and OCS behavior is presented in Section 3.3.

We have identified two periods, at the beginning and end of the flight, that indicate biomass burning signatures. Both were detected in close horizontal (latitudinal/longitudinal) proximity and within a comparable vertical range, characterized by pressure altitudes of 195–260 hPa and potential temperatures of 315–335 K indicating injection at similar isentropes. This spatial coincidence suggests that the observed signatures are part of the same air mass, implying a common origin of emission. In the remainder of the paper, we focus our analysis on the biomass burning signatures at the beginning of the first leg at about 216 hPa, where the plume was observed continuously for a period of the flight track corresponding to about 600 km horizontally.

Understanding whether the air masses associated with the observed biomass burning signatures are still in the troposphere or have already reached the stratosphere is crucial for assessing the impact on the atmosphere, such as the formation of stratospheric aerosols involving OCS. To separate tropospheric and stratospheric air masses, we use N_2O as a stratospheric tracer due to its long chemical lifetime of 110–120 years (Krysztofiak et al., 2023) and thus an almost constant value in the troposphere with decreasing values in the stratosphere (Müller et al., 2015). As shown in Figure 2a, we categorize all measurement data as stratospheric if they fall below the tropospheric background level. This threshold is derived from the measured value of 331.6 ppbv from the ground station in Ushuaia, Argentina, in November 2019 (NOAA, 2025). This value is reduced by the combined measurement uncertainty of 0.5 ppbv (1σ) for UMAQS and Ushuaia station measurements to ensure conservative classification of the stratospheric fraction. Applying a threshold of N_2O = 331.1 ppbv we find that the observed fire plume is partly located in the upper troposphere but predominantly located in the lower stratosphere (Figure 2b). This clearly indicates transport of biomass burning emissions into the stratosphere. In the next section, we use ERA5 reanalysis and satellite data to pinpoint the emissions' geographic origin.

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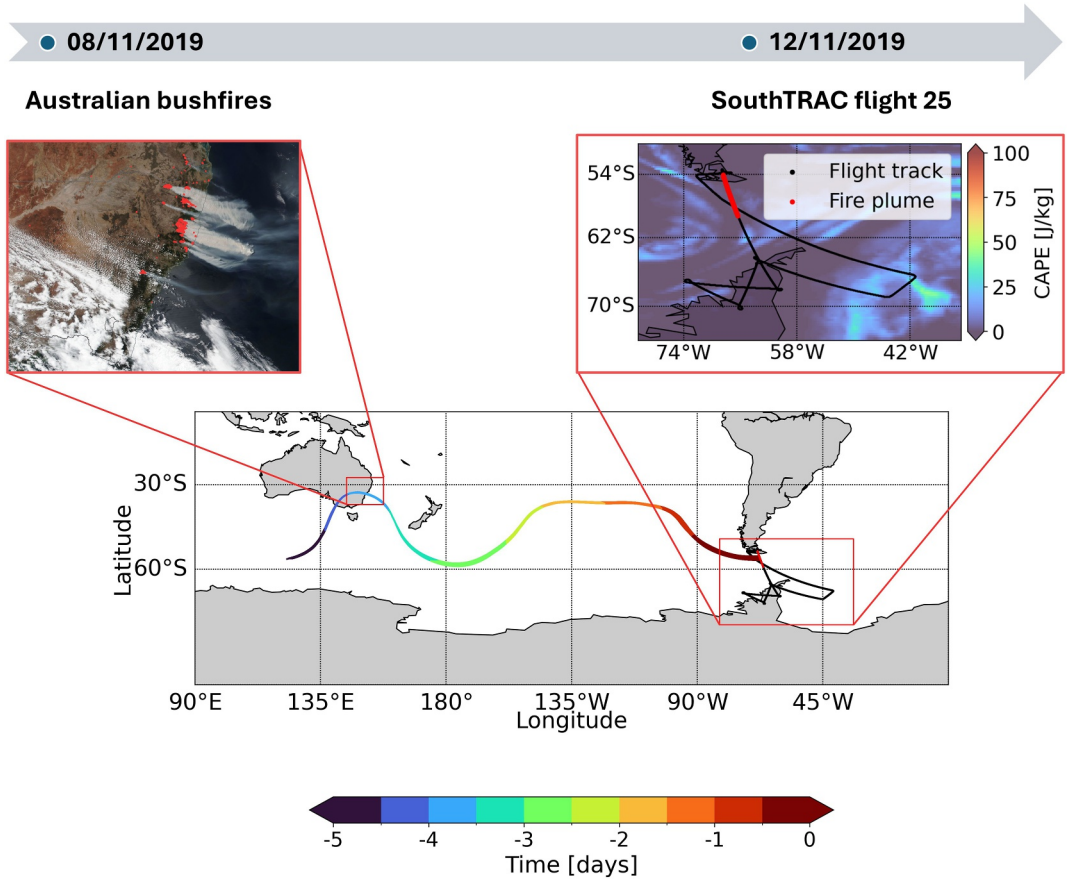

Figure 3. Lower panel: Backward trajectories started from the flight track (upper right) between 11:42–11:54 UTC during enhanced biomass burning tracer signatures of ST25. Satellite data from VIIRS at Suomi NPP observed on 8 November 2019 (upper left, NASA EOSDIS Worldview, 2025) indicate several biomass burning events marked with red dots in this region forming a fire plume moving eastwards.

3.2. Australian Bushfires: Origin of Biomass Burning Signatures

The in situ measurements during ST25 suggest the presence of biomass burning signatures in the stratosphere, potentially originating from either a local or remote source. A local emission source in South America is unlikely. First, there are no indications of convective activity upwind of the measurements that could transport local surface emissions from southern South America into the lower stratosphere (upper right panel, Figure 3). Second, the absence of NO enhancement suggests a plume aged over the course of several hours to days, indicating a more distant source.

To further investigate the potential origin of the observed plume, we combine ERA5 reanalysis data, backward trajectory analysis, and satellite observations. We performed a trajectory analysis using LAGRANTO driven by the three-dimensional wind from ERA5 to identify an emission source upwind of our observations. For this, we divided the flight path into 12-min segments, launching 720 trajectories along each segment—effectively one trajectory per second. Exactly for the time period of the detected biomass burning signatures, the trajectories show a coherent air flow during the 5 days prior to the observations (lower panel of Figure 3). Moreover, they cross the coastline of South-Eastern Australia roughly 4 days prior to the measurements on 8 November 2019. At this time, there were several wildfires near to the South-Eastern coast of Australia in the region New South Wales as indicated by the satellite image (upper left panel, Figure 3). The fires occurred at the start of the Australian bushfire season in summer 2019/2020, which explains the clear separation from the clean background air masses. Consequently, we can attribute the biomass burning signatures observed during ST25 over the Drake Passage to the propagating plume of the Australian bushfires.

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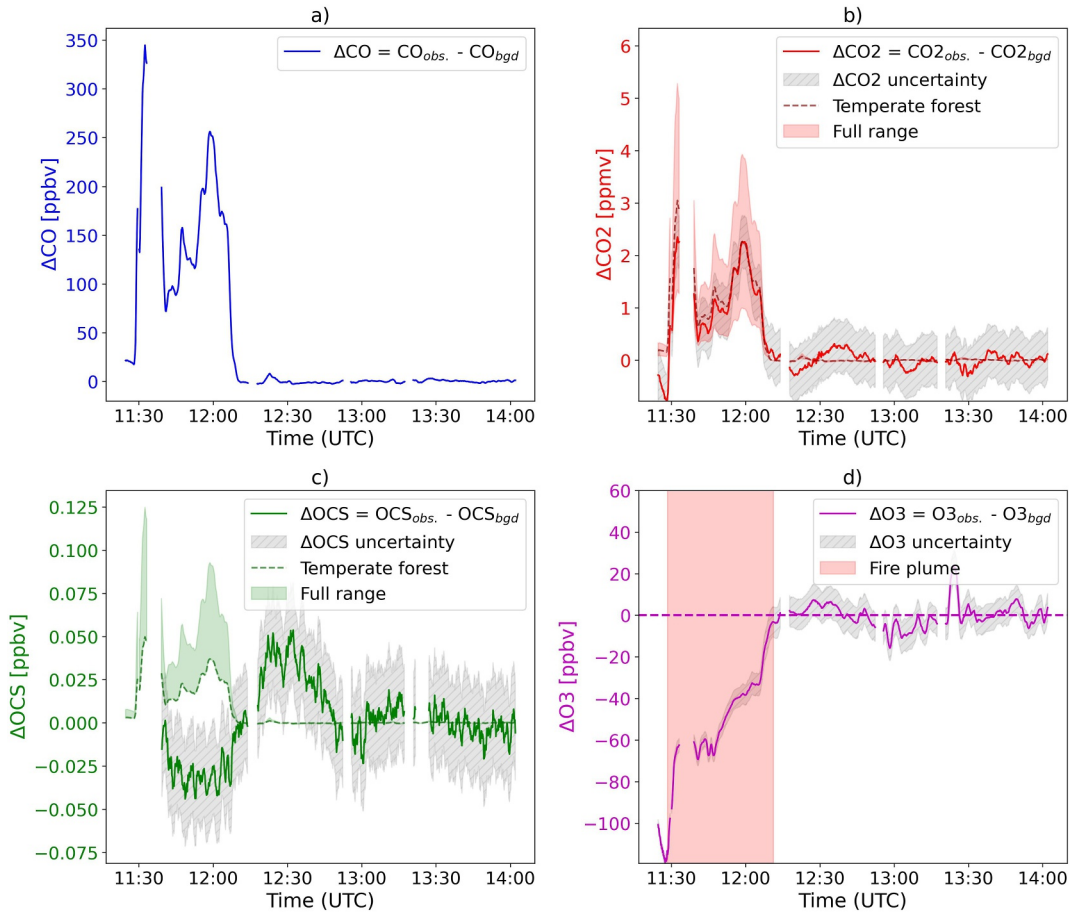

Figure 4. Enhancements in fire plume without background for CO, CO_2, OCS and O_3. Expected values for CO_2 and OCS related to CO were shown for the full range of vegetation types and for temperate forest (b, c). For O_3, the red shaded area highlights the time range of the fire plume (d).

While the detailed mechanisms of the fire plume transport into the stratosphere over the Drake Passage are beyond the scope of this paper, trajectory analysis provides insights into the air mass pathways and timescales. Changes of potential vorticity and potential temperature, as well as increased turbulence potential as indicated by low Richardson numbers, suggest diabatic transport and mixing along the trajectories (Figure S1 in Supporting Information S1). Consequently, the air masses may have entered the stratosphere in a two-step process: initial injection into the upper troposphere or lowermost stratosphere over Australia by pyro convection, followed by gradual ascent across the tropopause during eastward transport. However, the possibility of direct injection of the fire plume air masses into the stratosphere over Australia cannot be excluded.

3.3. Emission Profile of Australian Bushfires: No Enhancement in OCS and O_3

Given the south-eastern Australian origin, we can assume that the predominant burnt vegetation types were grass and eucalyptus trees (Deb et al., 2020). Consistent with the plume transport time derived from the trajectories, we estimate the age of the plume to be approximately 4 days. In the following, we will use the fire origin type and the estimated plume age to quantify the chemical composition of the fire plume against expected theoretical values to investigate the role of the Australian bushfires and, consequently, biomass burning in general as a source of OCS.

We use the specific (anti-)correlations with N_2O in the stratosphere to determine the enhancements compared to the stratospheric background for each species. To achieve this, we define the background for a specific N_2O mixing ratio in the fire plume as the corresponding value from the linear regression to the N_2O correlation (as illustrated in Figures 2d and 2f for CO/OCS). Finally, we determine the enhancements for a species X by removing the background in the plume (Figure 4, solid line):

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$$\Delta X = X_{\text{obs.}} - X_{\text{bgd}}. \tag{1}$$

We apply emission factors (EFs) from Andreae (2019), defined as species mass emitted per burned mass, to estimate fire emissions. Although the emission factors are determined for fresh plumes, we assume they remain representative of the 4-day-old fire plume given the multi-day atmospheric lifetimes of CO, CO_2 and OCS. The coherent transport behavior as indicated by the plume trajectories confirm this assumption, as the probability of mixing with other air masses is low. For the Australian bushfires, based on their geographical provenance, we primarily use the emission factors for "temperate forest" (i.e., EF_{CO} = 113.0 g/kg, EF_{CO_2} = 1,570 g/kg, EF_{OCS} = 0.035 g/kg). We also consider the full range of literature values across vegetation types (EF_{CO} = 76–260 g/kg, EF_{CO_2} = 1,430–1,660 g/kg, EF_{OCS} = 0.025–0.11 g/kg) to account for uncertainties in the type of burned vegetation, enabling a robust assessment of the data irrespective of specific biomass composition.

We represent the theoretically expected values for a species X relative to CO as a clear biomass burning tracer by using the molar mass M to facilitate a comparison between the emission factors ascribed in the extant literature and the measured enhancements:

$$\Delta X_{\text{theory}} = \Delta \text{CO} \cdot \frac{\text{EF}_X}{\text{EF}_{\text{CO}}} \cdot \frac{M_{\text{CO}}}{M_X}. \tag{2}$$

As expected, CO shows a clear enhancement in the fire plume in Figure 4a. The enhancement in CO with an approximate ratio of 9–10 compared to the background demonstrates its function as a tracer for biomass burning. In Figures 4b and 4c, the obtained theoretical enhancements are visualized for CO_2 and OCS. As can be seen from the data presented in Figure 4b, we observed an enhancement in the fire plume for CO_2 similar to that for CO. Moreover, the observed CO_2 enhancement aligns with the CO-derived predictions of Equation 2, falling predominantly within its theoretically defined range across all vegetation types. Specifically, the expected enhancement values for CO_2 are in close agreement with those for a temperate forest, as demonstrated by the mean relative difference of only around 9%–10%. Consequently, we can confirm the theoretical values for CO_2.

In contrast, OCS shows a decrease compared to the background values (Figure 4c). Even when accounting for measurement uncertainties of 27.5 pptv, the expected enhancements according to literature are not within the specified range for all vegetation types derived from our measurements. This discrepancy is emphasized by the mean relative deviation, which is nearly three times the expected value. Thus, we conclude that OCS has not been emitted from the Australian bushfires in significant amounts consistent with the lower enhancement values from Blake et al. (2004) for South-East Asia.

A potential explanation for the observed decrease in OCS could be chemical degradation of OCS along the transport path of the fire plume. However, given the lifetime of OCS of approximately 2 years in the troposphere (Montzka et al., 2007) and 70 years in the stratosphere (Karu et al., 2023), we consider the likelihood of such chemical degradation processes of OCS to be low. Nevertheless, our measurements only reflect one specific biomass burning event in a limited time range. We could have detected an instance of biomass burning events in which no or a negligible amount of OCS is emitted. Due to the broad range of burning vegetation types, it is possible that these instances were not covered by the study by Andreae (2019). A comparison with the NEIVA database (Binte Shahid et al., 2024) yields slightly lower expected emission enhancements of OCS (around 32% lower), though still above our measurements. Repetitive measurements of fire plumes in different vegetation types for a better differentiation of biomass burning events in future could be necessary to better understand the role of biomass burning as source of OCS.

For O_3, we observed a decrease in the mixing ratio for the air masses belonging to the fire plume (Figure 4d). In principle, the production of ozone in biomass burning plumes in the troposphere can be expected (Jaffe & Wigder, 2012). We hypothesize that the lower ozone levels are predominantly caused by dynamical effects. The plume originated from the troposphere and thus contained less ozone and as such represents a negative anomaly for ozone in the lower stratosphere. For the western Canadian wildfires in 2017, simulations confirmed this effect for ozone decrease (Yu et al., 2019). Note that we observed ozone production in the fire plume, as indicated by the positive correlation between CO and O_3 (Figure 2e). Inspection of the N_2O-O_3 correlation (not shown) suggests that mixing occurred between tropospheric and stratospheric air masses with an N_2O mixing ratio of 315 ppbv. It

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is therefore conceivable that the observed ozone mixing ratios were caused by a superposition of ozone production and dilution due to mixing.

4. Conclusion and Outlook

We investigated whether the Australian bushfires from November 2019 acted as a source of OCS in the atmosphere, which is generally a critical uncertainty in atmospheric models for climate research and the aerosol budget. By combining airborne in situ measurements during ST25 with a trajectory analysis, we identified a 4-day-old plume from the Australian bushfires localized in the lowermost stratosphere, enabling the analysis of fire emissions. It was observed that there were significant enhancements of carbon monoxide (CO) and of carbon dioxide (CO_2) in the fire plume itself. Furthermore, the enhancement of CO_2 was almost entirely in line with the anticipated literature findings relative to CO.

Conversely, a decrease compared to background values is observed in the case of OCS and O_3. Thus, we conclude that OCS is not substantially emitted from the Australian bushfires. Moreover, the observed mixing ratios of OCS do not confirm the anticipated theoretical literature values that predict OCS emissions from all burned vegetation types.

The findings of this study challenge the assumption that biomass burning is a universal source of OCS across all vegetation types. For modeling and further applications, an adjustment of the emission factors for OCS may be warranted advising caution when considering biomass burning as a source of OCS. However, our results are only constrained to a single biomass burning event, which highlights the need to observe additional events to assess the global impact of biomass burning on OCS.

To resolve the apparent discrepancy between observed OCS behavior and literature values, future research could utilize measurements of OCS in fire plumes originating from diverse geographical regions (e.g., tropical, boreal, temperate forests), to improve our understanding of the emission of OCS in diverse vegetation types. Our measurements from SouthTRAC flight 19 on 7 October 2019, which encountered a tropical forest fire plume, also suggest a slight decrease in OCS mixing ratios, which aligns with the results from our analysis of the Australian bushfire plume (Figure S2 in Supporting Information S1). Moreover, systematic measurements of fire plumes at various transport stages (e.g., near-source, during transport, and in the stratosphere) will clarify whether OCS decreases originate from minimal emissions at the source or from degradation processes during transport. Revised OCS emission factors would improve atmospheric models and climate research predictions, thereby providing insights into effective strategies to mitigate the impact of biomass burning on climate change. Thus, our results contribute to a more precise understanding of the role of OCS in atmospheric chemistry.

Conflict of Interest

The authors declare no conflicts of interest relevant to this study.

Availability Statement

The data and software code used to generate the plots in this study are available on Zenodo at https://doi.org/10.5281/zenodo.16942290 (Kessler, 2026). ERA5 reanalysis data is openly accessible at Copernicus Climate Change Service, Climate Data Store, from the European Centre for Medium-Range Weather Forecasts via https://doi.org/10.24381/cds.143582cf (Hersbach et al., 2017). Surface N_2O data from Ushuaia, Argentina, is freely available at the Global Monitoring Laboratory from the National Oceanic and Atmospheric Administration (NOAA), U.S. Department of Commerce via https://gml.noaa.gov/aftp/data/trace_gases/n2o/flask/surface/txt/n2o_ush_surface-flask_1_ccgg_month.txt (NOAA, 2025, last access: 08/27/2025).

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