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Investigating the vertical extent of the 2023 summer Canadian wildfire impacts with satellite observations

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Abstract. Pyrocumulonimbus clouds (pyroCbs) generated by intense wildfires can serve as a direct pathway for the injection of aerosols and gaseous pollutants into the lower stratosphere, resulting in significant chemical, radiative, and dynamical changes. Canada experienced an extremely severe wildfire season in 2023, with a total area burned that substantially exceeded those of previous events known to have impacted the stratosphere (such as the 2020 Australian fires). This season also had record-high pyroCb activity, which raises the question of whether the 2023 Canadian event resulted in significant stratospheric perturbations. Here, we investigate this anomalous wildfire season using retrievals from two satellite instruments, ACE-FTS (Atmospheric Chemistry Experiment – Fourier Transform Spectrometer) and OMPS LP (Ozone Mapping and Profile Suite Limb Profiler), to determine the vertical extents of the wildfire smoke along with chemical signatures of biomass burning. These data show that smoke primarily reached the upper troposphere but only a nominal amount managed to penetrate the tropopause. Only one ACE-FTS occultation captured elevated concentrations of biomass burning products in the lower stratosphere on July 30th, and back and forward trajectories place the source fire in the Yukon. However, OMPS LP aerosol measurements indicate that any smoke that made it past the tropopause did not last long enough to significantly perturb stratospheric composition. While this work focuses on Canadian wildfires given the extensive burned area, pyroCbs at other longitudes (e.g. Siberia) are also captured in the compositional analysis. These results highlight that despite the formation of many pyroCbs in major wildfires, those capable of penetrating the tropopause are extremely rare; this in turn means that even a massive area burned is not necessarily an indicator of stratospheric effects.

1 Introduction

In 2023, a record-breaking fire season burned over 45 million acres in Canada, almost ten times the 1983 – 2022 annual average burned area of 5.2 million acres (Canadian Interagency Forest Fire Centre Inc., https://ciffc.net/statistics/). These events follow a trend of increasingly extensive and destructive wildfires, often referred to as megafires, that are projected to become more frequent under a changing climate (Di Virgilio et al., 2019; Williams et al., 2019; Pausas and Keeley, 2021). In

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addition to the well-studied impacts of megafires on air quality and tropospheric composition, a number of events have also injected wildfire smoke into the stratosphere via deep convective events known as pyrocumulonimbus clouds (pyroCbs) (Fromm et al., 2010; Fromm et al., 2019; Fromm et al., 2022).

PyroCbs are towering thunderstorms triggered by intense surface fire activity that also require specific meteorological conditions for development (including very dry surface conditions and high moisture and instability in the mid-troposphere, see Peterson et al., 2017). Some pyroCbs can perturb stratospheric composition in a manner similar to volcanoes. Perhaps the most notable example of these effects is the 2019 – 2020 Australian New Year Super Outbreak (ANYSO) event that injected up to 1.1 Tg of smoke into the stratosphere (Khaykin et al., 2020; Peterson et al., 2021). ANYSO, which was part of the Australian "Black Summer" bushfire season where over 14 million acres burned, has been linked to stratospheric ozone depletion and numerous climate impacts (Boer et al., 2020; Kablick et al., 2020; Rieger et al., 2021; Bernath et al., 2022; Solomon et al., 2023). While the Black Summer fires raged for about seven months, nearly all the stratospheric input occurred on just a few days; December 29-31, 2019 and January 4, 2020. (Davey and Sarre, 2020; Khaykin et al., 2020; Peterson et al., 2021). Stratospheric perturbations also occurred as a result of the 2017 Pacific Northwest Event (PNE) in British Columbia, when on August 12, 2017, pyroCbs injected an estimated 0.3 Tg of aerosols into the stratosphere (Peterson et al., 2018; Torres et al., 2020). For context compared to 2023, the 2017 Canadian wildfires burned a total of 8.6 million acres, with over 3 million acres burned in British Columbia (Government of British Columbia, https://www2.gov.bc.ca/).

Given the outsized area burned in the 2023 Canadian wildfires, significant stratospheric impacts perhaps as in the PNE or ANYSO events might be expected. It has been reported that at least 135 pyroCbs occurred in Canada between May and August 2023, a record-high amount further suggesting the possibility of substantial perturbations to stratospheric composition (NASA EarthData, https://www.earthdata.nasa.gov/). Recent research has investigated the tropospheric impacts of the 2023 fires, identifying record-high particulate matter emissions with implications for air quality and human health, but the vertical extent of these impacts and whether smoke entered the stratosphere has not yet been reported (Thurston et al., 2023; Wang et al., 2023).

The Atmospheric Chemistry Experiment – Fourier Transform Spectrometer (ACE-FTS) is a satellite instrument that detects a number of species including multiple biomass burning tracers with high sensitivity and precision (Sect. 2.1). Here, we use data from ACE as well as aerosol extinction data from the Ozone Mapping and Profiler Suite Limb Profiler (OMPS LP), described in Sect. 2.2, to investigate whether the 2023 Canadian wildfires perturbed stratospheric composition. These data products, combined with back and forward trajectories from the NOAA Hybrid Single-Particle Lagrangian Integrated Trajectory (HYSPLIT) model as detailed in Sect. 2.3, are then used to connect chemical signatures of stratospheric smoke to potential source fires.

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2 Data and methods

2.1 ACE-FTS and MLS data

ACE-FTS aboard the Canadian ACE/SCISAT-1 platform is a solar occultation instrument that collects up to 30 daily atmospheric absorption measurements at sunrise and sunset using the Sun as a light source (Bernath, 2005; Bernath, 2017). The infrared Fourier transform spectrometer measures over a wide spectral range (750 to 4400 cm^{-1}) with a high resolution of 0.02 cm^{-1} and signal-to-noise ratio ranging between 100:1 and 400:1 (Buijs et al., 2013). The ACE-FTS processing version 5.2 provides vertical volume mixing ratio (VMR) profiles for 46 molecules and 24 isotopologues including characteristic biomass burning indicator molecules such as carbon monoxide (CO), hydrogen cyanide (HCN), acetonitrile (CH_3CN), and ethane (C_2H_6) (Boone et al., 2023). A pair of filtered imagers also measures atmospheric extinction at two wavelengths: visible (VIS, 527.11 nm) and near-infrared (NIR, 1020.55 nm). The NIR imager is less likely to become saturated in cases of strong aerosol extinction and was thus used in this analysis for detection of aerosol loads (Boone et al., 2020). Temperature profiles are also collected with every occultation measurement and were used to calculate tropopause heights as defined by the WMO: the lowest altitude at which the lapse rate decreases below 2 K km^{-1} (WMO, 1957). Data from ACE are available at https://databace.scisat.ca/level2/ace_v5.2/ starting from 2004.

Given the limited data coverage of ACE, we compare its CO measurements to data from the Microwave Limb Sounder (MLS) aboard the NASA Aura satellite. The MLS instrument has seven radiometers that measure microwave thermal emissions between 118 GHz and 2.5 THz from the limb of the atmosphere to determine vertical profiles of atmospheric constituents. This instrument has a much higher spatial coverage than ACE, but the use of microwave spectroscopy provides data with a lower signal-to-noise ratio on individual soundings and a more limited vertical range. For example, the CO data product is recommended for scientific use between 215 – 0.001 hPa, while the HCN and CH_3CN valid ranges are even smaller at 21 – 0.1 hPa and 46 – 1.0 hPa respectively (Livesey et al., 2022). Thus, we compare ACE and MLS CO profiles to validate the robustness of our results (Fig. S1). We find through this comparison that the volume mixing ratios from the two instruments are within reasonable agreement of each other, but MLS is not as useful for our analysis given the lack of reliable data, particularly for individual soundings, at our pressure range of interest in the lowermost stratosphere. Data from MLS are available at https://disc.gsfc.nasa.gov/datasets/ML2CO_NRT_005/summary starting from 2004.

2.2 OMPS LP data

OMPS LP on the Suomi NPP satellite is a limb profiler that measures scattered UV, visible, and near-IR radiation. Aerosol extinction coefficients are retrieved for six wavelengths (510, 600, 675, 745, 849, and 997 nm) with the V2.1 algorithm (Taha et al., 2021). OMPS LP measures along Earth's limb with three parallel vertical slits, one central slit that views along the nadir track and two side slits viewing with a cross-track separation of 250 km at the tangent point allowing for near-

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global daily coverage. The 745 nm channel was used in this analysis given its high sensitivity to aerosol loading and low bias. Data from OMPS is available at https://disc.gsfc.nasa.gov/datasets/OMPS_NPP_LP_L2_AER_DAILY_2/summary starting from 2012.

2.3 NOAA HYSPLIT

NOAA HYSPLIT is a trajectory model developed by the National Oceanic and Atmospheric Administration Air Resources Laboratory (NOAA ARL) that is used to simulate atmospheric transport, dispersion, and deposition of pollutants (Stein et al., 2015). The model is compatible with numerous meteorological datasets and in this study was run on reanalysis data from the National Centers for Environmental Prediction (NCEP) Global Forecast System (GFS) 0.25 degree grid. Trajectories are initialized from an air parcel defined by its altitude, latitude, longitude, and time and run for a prescribed time period. The model is available at https://www.ready.noaa.gov/HYSPLIT.php.

3 Results and discussion

3.1 Chemical signatures for biomass burning

The tropopause acts as a strong barrier to troposphere-to-stratosphere transport, and the high vertical resolution of ACE is useful in determining whether smoke entered the stratosphere. Individual occultation measurements from ACE provide simultaneous constituent volume mixing ratio (VMR) and temperature profiles where biomass burning product concentrations can be compared against self-consistent tropopause heights as measured on the same occultation and in broader averages. HCN is a robust wildfire tracer for the Northern hemisphere because its primary source is biomass burning (Li et al., 2000, Roberts et al., 2020). In contrast, other tracers like CO and ethane are emitted in large amounts by both wildfires and anthropogenic sources such as transportation and industry (Xiao et al., 2004), complicating source attribution for those compounds. We first compare average monthly HCN volume mixing ratio (VMR) profiles in 2023 to monthly averages across the rest of the ACE-FTS measurement period (2004 to 2022) in the region from 40° to 70°N to identify when anomalous concentrations occur that are very likely associated with wildfires. Chemical signatures detected in this latitude range also reflect other active wildfire regions such as Siberia (MODIS, https://modis.gsfc.nasa.gov/). Figure 1 suggests an enhancement of HCN in the upper troposphere and lowermost stratosphere (UTLS) between June and September 2023 relative to what is typical in preceding years, with the monthly average tropopause heights calculated from ACE-FTS temperature profiles representing a rough delineation between the troposphere and stratosphere. But on average, significant enhancements do not extend more than a few kilometers above the tropopause. Similar results can be seen for single profiles (Fig. S2).

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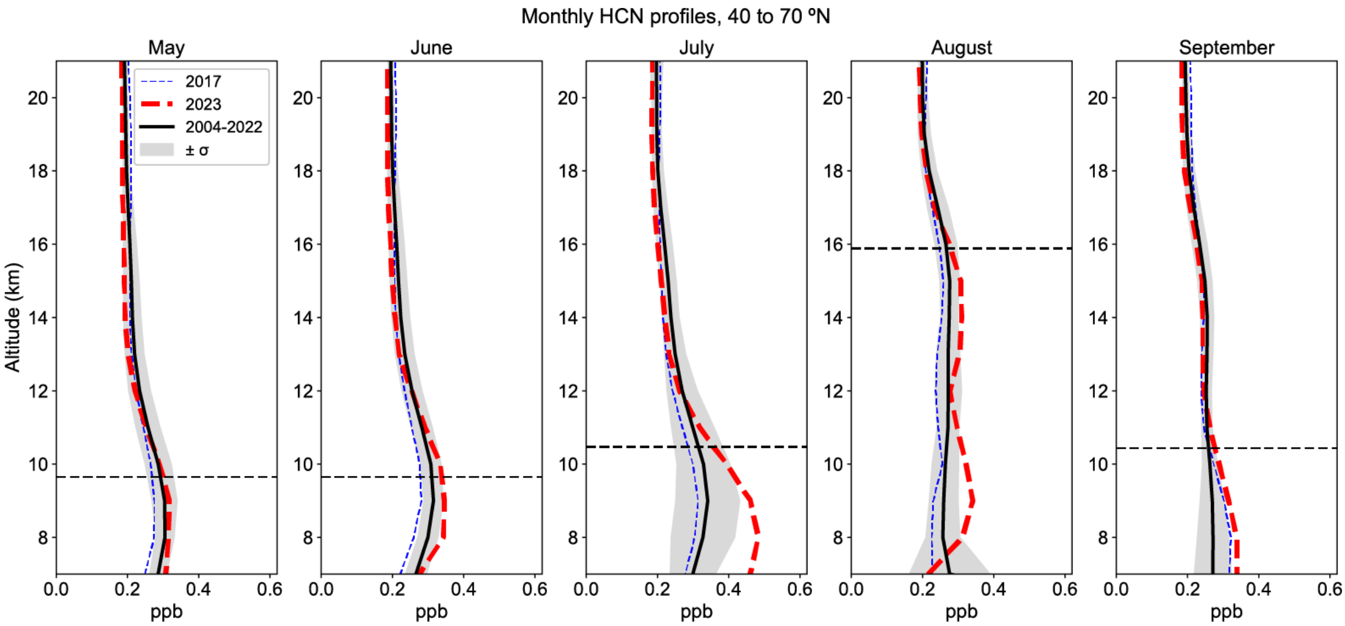

Figure 1: Monthly average HCN profiles from 40 to 70° N measured by ACE-FTS. The red curves show monthly averages in 2023, and the black curves show monthly averages from 2004–2022 with the grey shaded area representing ± one standard deviation from the 2004–2022 average. 2017 is differentiated by the blue dashed line as it was an anomalous year with the PNE. The approximate monthly average lapse rate tropopause altitudes calculated for 2023 are plotted for reference.

ACE/SCI-SAT1 takes a limited number of measurements over our latitude range of interest during August (Table S1); in 2023, measurements were only taken on the first couple days of the month and between 40 and 45° N. This may explain the unusually high tropopause altitude for this month as such limited temporal and spatial scales are more subject to the influence of external processes such as the Asian monsoon (Basha et al., 2020). The range given by the standard deviation of ACE data from 2004 to 2022 indicates that there were likely other wildfire years that also produced high HCN concentrations from June to September, but 2023 is on the upper end of this spread from about 8 to 11 km. July 2023 in particular has noticeably higher concentrations compared to the range of previous years. Although this HCN enhancement is indicative of wildfire smoke reaching the upper troposphere, the occurrence of stratospheric injection is less clear given the variability of tropopause heights and the limited number of observations, particularly in August (see Table S1).

The average July 2023 profiles of other biomass burning markers such as CO, CH_3OH, HCOOH, and C_2H_6, also exhibit elevated concentrations in the upper troposphere but not significantly so in the lowermost stratosphere. These data provide strong evidence for the vertical transport of wildfire smoke to the upper troposphere due to high pyroCb activity during the summer wildfire season. However, significant stratospheric penetration is not observed (Fig. 2).

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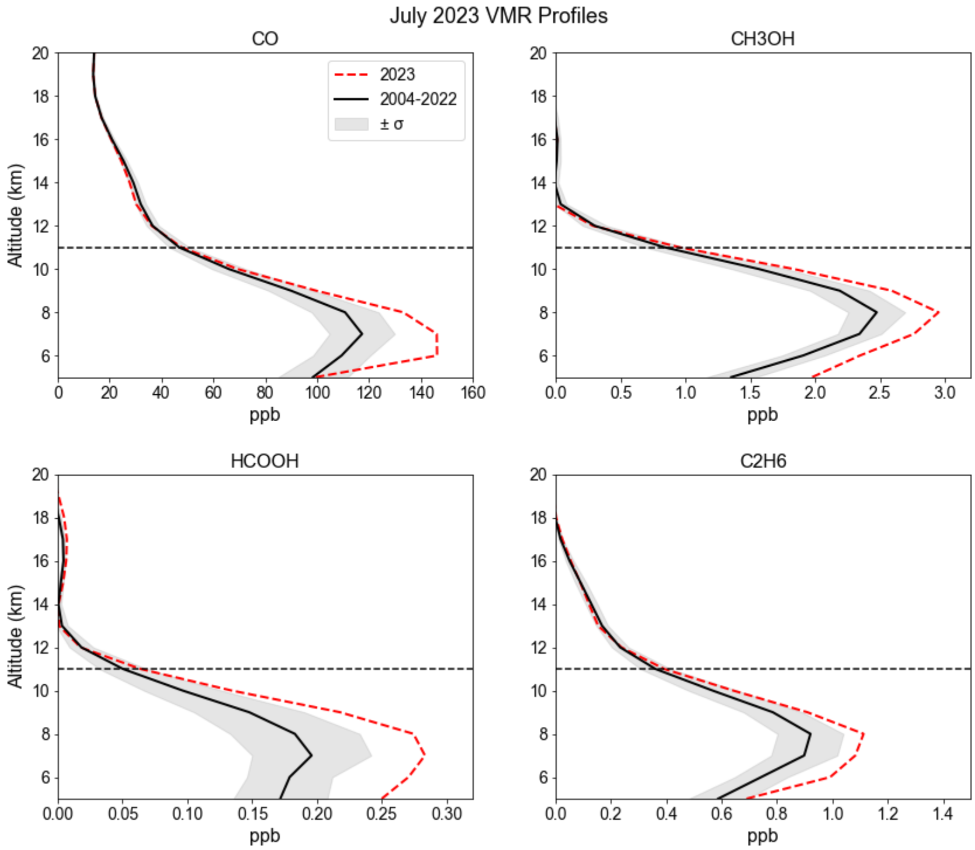

Figure 2: Average July 2023 VMR profiles for additional biomass burning tracers: CO, CH_3OH, HCOOH, and C_2H_6, plotted against 2004–2022 July averages over 40º N to 70º N. The grey shaded area represents ± one standard deviation based on 2004–2022 data.

3.2 Occultation ss107570

Inspection of every individual occultation measured by ACE-FTS over the 40 to 70º N latitude band in July 2023 revealed one occultation measurement indicative of stratospheric injection because it exhibited both clear chemical signatures and aerosol extinction above the tropopause (Fig. S2). This measurement, ss107570, was taken on July 30th 04:26 UTC over 49.14º N, 132.10º W off the coast of British Columbia, and the profiles are shown in Fig. 3. The temperature profile retrieved with this occultation indicates a lapse rate tropopause at around 10 km.

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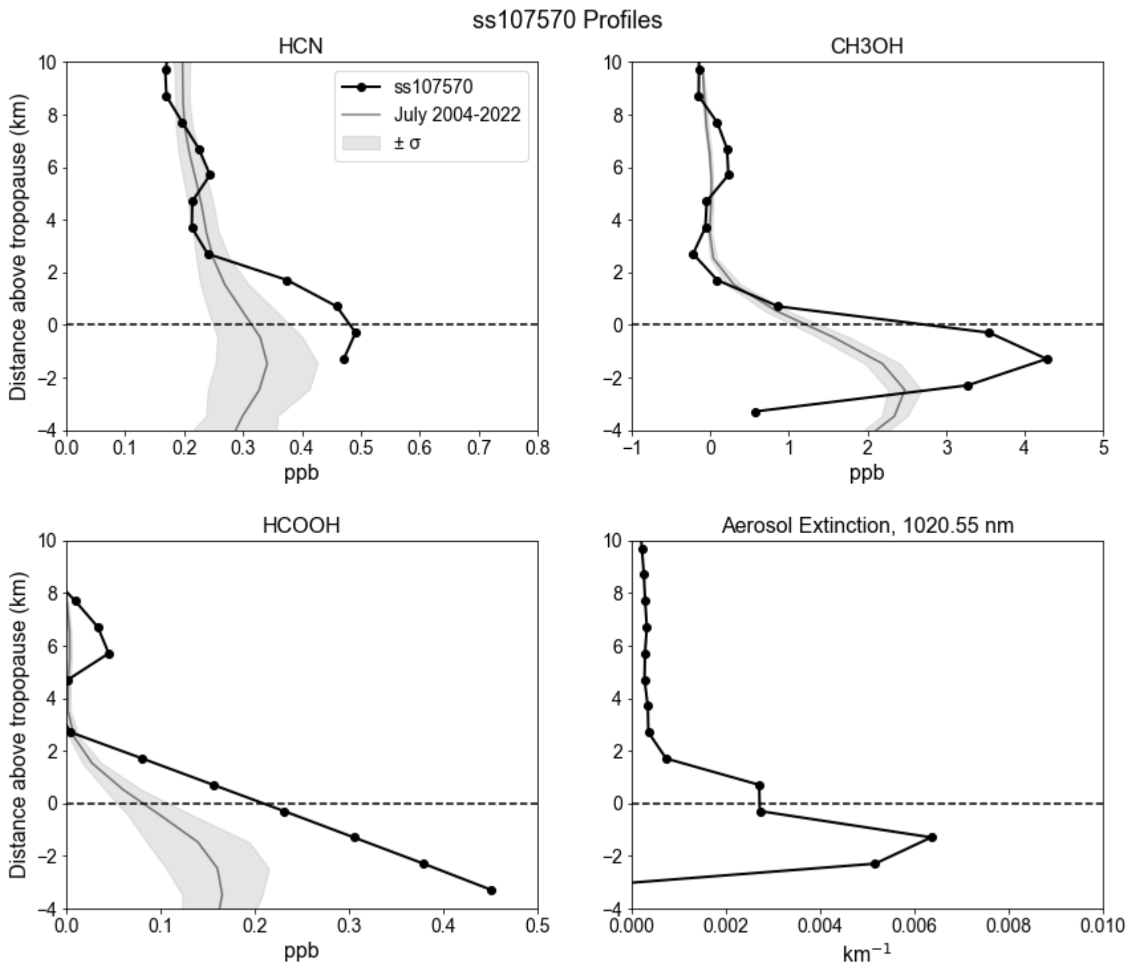

Figure 3: Biomass burning product VMR and aerosol extinction profiles for occultation ss107570, which all exhibit enhanced concentrations in the lower stratosphere. The July 2004 – 2022 averaged profiles of the gaseous products are plotted for reference with the altitude adjusted to distance above tropopause height.

Elevated concentrations of multiple biomass burning products measured above the tropopause in ss107570 offer evidence for wildfire smoke entering the stratosphere in late July. To further validate this conclusion, the ACE infrared absorption spectrum was also analyzed for features characteristic of wildfire smoke, as in Boone et al. (2020). Carbonaceous aerosols typically exhibit C–H, O–H, and C–C features associated with alkanes and oxygenated organics, and these are indeed present on this occultation as shown in the IR spectrum in Fig. 4 (Zhong and Jang, 2014; Boone et al. 2020; Bernath, 2020). The O-H stretch is commonly seen in smoke particles and indicates that they are oxygenated (Boone et al., 2020). The C=O stretch, which is also associated with oxygenated smoke particles and identified using a feature around 1750 cm^{-1}, cannot be seen because that region is saturated.

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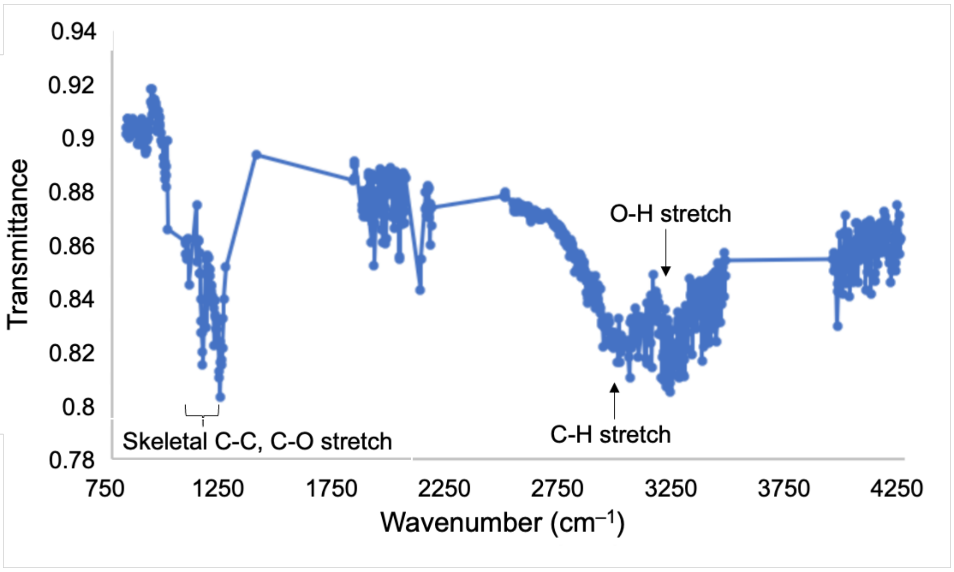

165 **Figure 4: Residual IR spectrum for ss107570 measured at a tangent height of 10.6 km. The highlighted features are indicative of smoke.**

3.3 OMPS LP Aerosol data

Aerosol extinction data from OMPS LP also indicate a small increase in aerosol burden in the lowermost stratosphere between 11.5 and 16.5 km, in late July 2023 (Fig. 5). However, this increase above background levels is both minor and short-lived, which indicates that not enough smoke was injected into the stratosphere to significantly impact extinction measurements. Throughout the entire wildfire season, there are no significant aerosol extinction signals at this altitude range that would suggest deep convective wildfire events. This validates our general finding that very little smoke managed to make it well above the tropopause despite high pyroCb activity, suggesting that the many convective events that occurred were mostly limited to the upper troposphere. There is a constant background level of aerosols above 65º N, but this feature is present from the beginning of 2023 and therefore is not linked to the 2023 Canadian wildfire events.

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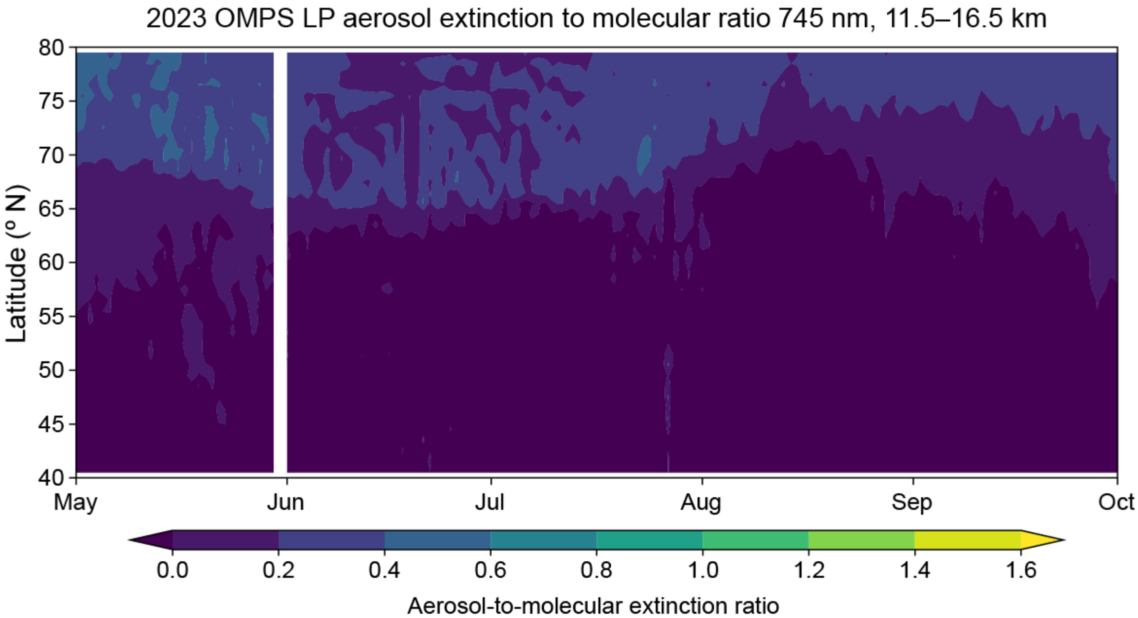

Figure 5: Zonally averaged daily OMPS extinction to molecular ratio between 11.5 and 16.5 km, 40 to 80º N. This represents the evolution of aerosol load in the lower stratosphere during the 2023 summer wildfires.

The altitude range between 10.5 and 11.5 km contains either tropospheric or stratospheric air depending on the latitude and time of year, and analysis of OMPS data at this altitude reveals substantial aerosol loading in the region around the tropopause in 2023 (Fig. S5, middle panel). This suggests that the many pyroCbs of the 2023 wildfire season alongside other aerosol sources managed to inject particles right around the tropopause. However, the significant decrease in signal past 11.5 km as seen in Fig. 5 constrains these inputs to the region at or just above the tropopause as opposed to higher in the stratosphere where more impacts would be realized.

3.4 Trajectory analysis

The preceding data provide evidence for stratospheric entry of smoke around the location and date of ss107570. Back trajectory analyses enable the identification of potential source fires that generated a pyroCb capable of direct stratospheric injection. 72 hour trajectories ending at the point of measurement were run on NOAA HYSPLIT and are shown in Fig. 6, with possible source fire locations concentrated in the Yukon and Northwest Territories.

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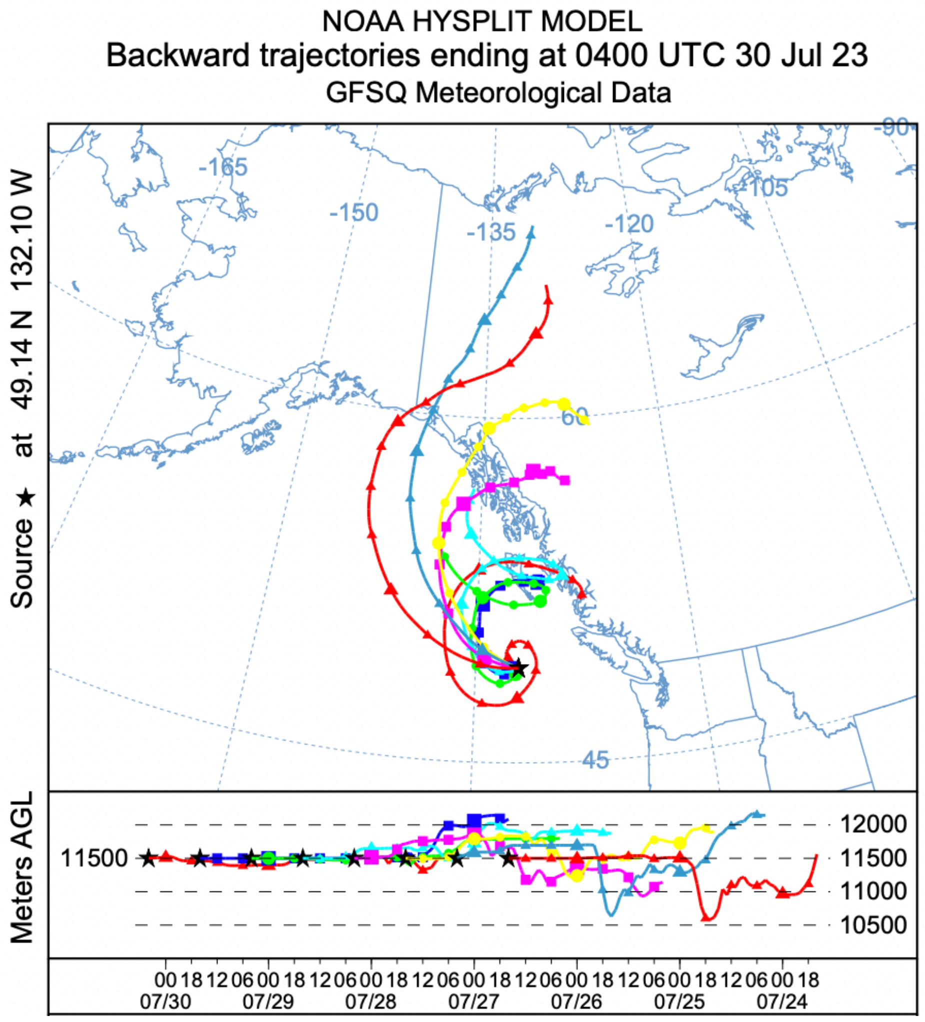

Figure 6: 72 hour HYSPLIT back-trajectories ending at the point of ACE-FTS measurement (49.14º N, 132.10º W) at 11.5 km. Trajectories are initialized from this location in 12 hour increments, with the latest start time occurring on July 30th, 2023 04:00 UTC (the time of measurement) and the earliest start time on July 26th 2023, 16:00 to compensate for limited ACE-FTS coverage.

Given the extent of Canada's wildfire season, using fire databases to identify potential source fires is non-trivial given the large number of events in 2023 with extensive burned areas (Canadian Interagency Forest Fire Centre Inc, https://ciffc.net/national). Thus, more targeted methods for identifying pyroCb-specific fires are a more promising approach for this analysis. Cross-referencing with an online crowdsourced pyroCb database (https://groups.io/g/pyrocb) suggests one event on July 24th in the Yukon, 63.00º N, 133.8º W, as a candidate event given its consistency with the trajectories in Fig. 5. Further, this pyroCb was reported to have a brightness temperature of –62.2 ºC, which is nearly 5 ºC lower than the cold point tropopause of -57.6 ºC (Fig. S3). A cold cloud top of this magnitude is indicative of deep overshooting convection that penetrates the tropopause and enters the stratosphere (Romps et al., 2009). It is therefore plausible that this pyroCb is the source of the plume measured by ss107570.

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Forward trajectories from the reported pyroCb location also pass through the measurement location of the ss107570 occultation (Fig. S4). This further establishes the connection between this Yukon event and the ACE-FTS measurement. It is important to note that these trajectories do not factor in pyroCb-driven convection itself but rather calculate paths of parcels that are passively carried by mean winds after they have already been convected to the stratosphere. Through these trajectory analyses we have identified one pyroCb that likely injected smoke into the stratosphere and is connected to the ACE-FTS measurement. However, the magnitude of such an event, alongside any other pyroCbs that managed to penetrate the tropopause but were not directly measured by ACE-FTS, did not have significant impacts on stratospheric composition or aerosol loading as seen in the other data shown here.

3.5 Comparison to Pacific Northwest Event

To contextualize the Yukon event, we compare its ACE-FTS profiles with measurements of the 2017 PNE which also occurred in western Canada during the summer. Analysis of this event was previously reported in Boone et al. 2020, with the occultation sr75758 probing the plume a few weeks after initial stratospheric injection. Figure 7 shows a substantial difference in plume altitude, with the 2017 PNE exhibiting chemical signatures of wildfire smoke up to 10 km above the tropopause compared to the ~1 km injection height of the 2023 Yukon event.

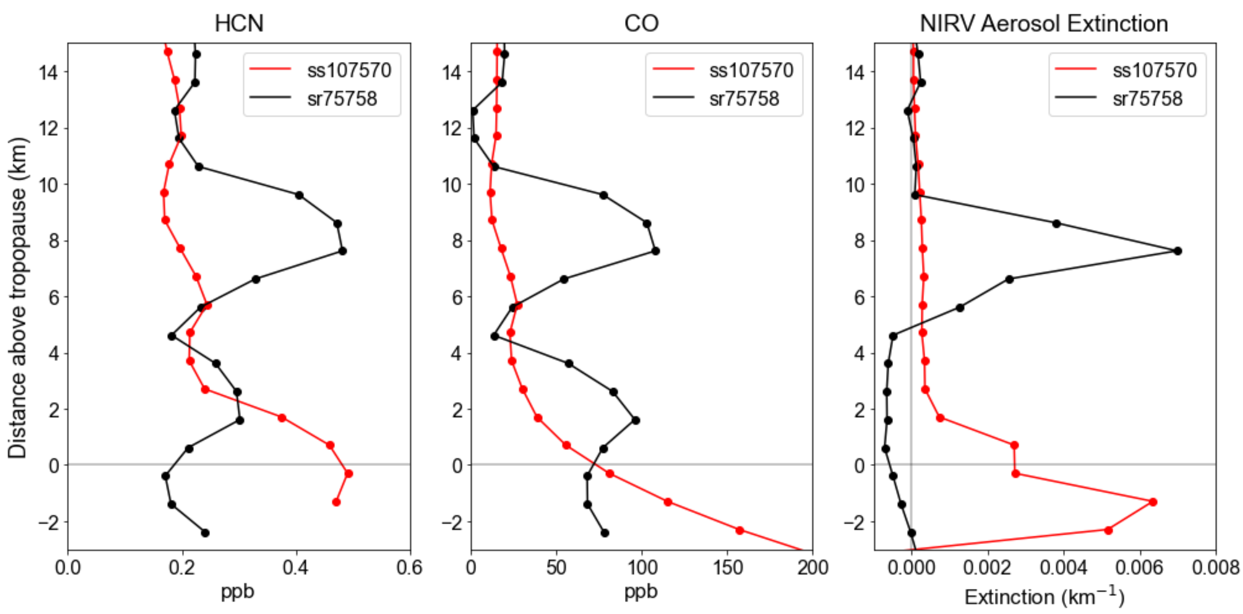

Figure 7: Biomass burning product VMR and aerosol extinction profiles for occultation sr75758 (black) associated with the 2017 Pacific Northwest Event (Boone et al., 2020). Profiles from the Yukon event measured by ss107570 are shown in red for comparison. The altitude is relative to the tropopause height, which was around 10 km for ss107570 and 13 km for sr75758.

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The maximum VMR and aerosol extinction values are similar between the two events, and Fig. S5 also shows that the aerosol loading near the tropopause is similar between the two years. However, the stratospheric impact of the PNE is visibly larger since the entire plume is measured well above the tropopause whereas only part of the Yukon plume is clearly in the stratosphere. This lower injection height corresponds to a shorter plume lifetime in the stratosphere, further suggesting the smaller impact of the Yukon event compared to the PNE (D'Angelo et al., 2022). The top panel of Fig. 8 shows that between 11.5 and 16.5 km, 2017 featured a much larger and longer-lasting injection of aerosols into the stratosphere relative to 2023 where there is no evident increase in average extinction throughout the entire summer. Similarly, the bottom panel of Fig. 8 contrasted to Fig. 5 shows that the magnitude and duration of stratospheric perturbation from the PNE was much more substantial than that of any pyroCb activity from 2023. Since ACE-FTS measured only one occultation with clear stratospheric signatures of smoke and the OMPS LP aerosol data does not feature any significant perturbations in 2023, we conclude that the 2023 Canadian wildfire season did not significantly impact stratospheric composition relative to previous years despite burning a far larger area and exhibiting frequent pyroCb activity.

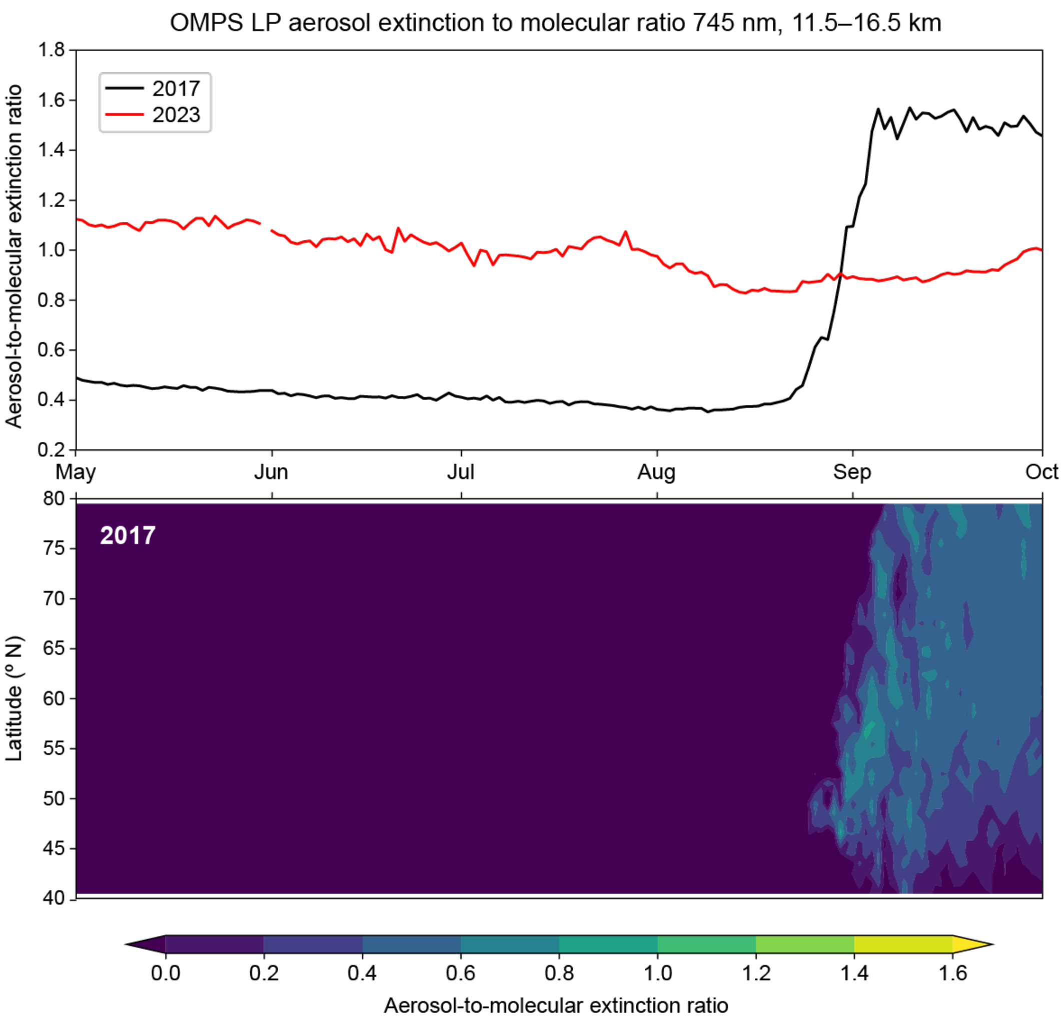

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Figure 8: Top panel: average OMPS aerosol-to-molecular extinction ratio from 40 and 80º N, 11.5 to 16.5 km compared between 2017 (black) and 2023 (red). Bottom panel: 2017 zonally averaged OMPS extinction between 11.5 and 16.5 km, 40 to 80º N.

4 Conclusions

Using ACE-FTS observations, we identified the presence of biomass burning products in the stratosphere in only one occultation measurement over Canada during the 2023 summer wildfire season, and back and forward trajectories linked these elevated concentrations to a pyroCb event on July 24th in the Yukon. This and other ACE constituent data, alongside the OMPS LP aerosol data, suggests that the immediate impacts of these fires are essentially limited to the troposphere. Any aerosols that made it into the stratosphere remained near the tropopause and did not make it high enough to substantially influence stratospheric composition. However, carbonaceous aerosol has the potential to increase parcel buoyancy via solar heating and self-loft over longer timescales (de Laat et al., 2012; Yu et al., 2019; Ohneiser et al., 2023). The impacts of this process have not been pursued in this work but may have implications for climate and stratospheric composition.

In summary, this work shows that despite an extremely extensive wildfire season with frequent pyroCb activity in Canada, the conditions for sufficiently deep convection were met so rarely and to such a limited extent that no significant stratospheric perturbation took place. These results highlight that area alone is not a useful indicator of the potential for stratospheric effects, and projected increases in area burned per degree of global warming are not enough to forecast the vertical extents of future wildfires. The complexity of intense pyroCb formation motivates further study of why certain events, such as the 2019 – 2020 ANYSO and 2017 PNE, are more primed for stratospheric penetration. Factors including fire intensity and atmospheric structure may play an important role. Understanding which wildfire conditions enable stratospheric impacts, and how and where these may be realized under a changing climate, has significant implications for stratospheric ozone and climate.

Competing interests

The contact author has declared that none of the authors has any competing interests.

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