Reply to Reviewer #2

We thank the Reviewer #2 for the positive review and fair remarks, which have all been carefully implemented in the manuscript.

General Comments

1. **Reconsideration of the PyroCb dominance statement (lines 45–50)**
   In light of the results presented, showing that out of 142 detected PyroCb events, only three (event #1 and partially events #6 and #7; Table 1) were associated with measurable stratospheric impact, the authors may wish to revisit their statement that PyroCb activity is the *primary* source of combustion products entering the stratosphere. It could be valuable to discuss whether the current findings are consistent with this prevailing view or whether alternative pathways, such as WCB transport, might warrant greater emphasis.

The statement regarding the dominance of the pyroCb pathway (among the other mechanisms invoked) in terms of the large-scale stratospheric impact of wildfires provided in the introduction reflects the state-of-the-art. The most significant large-scale perturbations of stratospheric aerosol load have indeed been unambiguously associated with direct pyroCb injections and this statement still holds true. In this study, we demonstrated the potential of WCB-driven uplift to deliver significant amount of smoke aerosols to the extratropical tropopause layer. The anomalously warm Boreal Summer 2023 characterized by incessant wildfire activity across Canada in combination with the WCB-favorable synoptic conditions over North America during August-September drove a sequence of WCB-driven uplift episodes that had a cumulative effect on the stratosphere comparable with (yet not exceeding) the largest single-event pyroCb injections. The disproportionally smaller stratospheric impact of the numerous pyroCb events during the 2023 season does not necessarily undermine the dominance of the pyroCb pathway. The physics and lifecycle of extreme pyroconvection are still poorly constrained and many questions remain regarding the factors and conditions permitting major pyroCb injections into the stratosphere.

2. **Potential human-induced biases in PyroCb detection (Section 2.2)**
   The manuscript notes the use of an "analyst-in-the-loop" approach for PyroCb identification (line 80) in the global database of 761 events (2013–2023). The authors could elaborate on any potential human-induced biases in this process. In particular, could such biases have contributed to under-detection of PyroCb events during August–October 2023?

There is a chance for missing a pyroCb by the analyst-in-the-loop process as a general matter. This even occurred in 2023: one additional pyroCb, in September, was identified months after the 2023 season end. However, for the period in question, that being mid-July to late-August 2023, we claim no bias potential because our analysis of

the curiously strong lower stratospheric aerosol signals reported in the manuscript involved multiple revisits of GOES imagery wherever fire hot-spots were in evidence for the unmistakable microphysical signals of a pyroCb. It was a review like this that led to our post-season detection of the single additional September pyroCb mentioned above. There were no relevant gaps in GOES coverage that could have made our search vulnerable to a missed pyroCb detection. We recognize the imperfect nature of analyst-in-the-loop pyroCb detection for domains and times for which no such scrutiny is demanded. But in this case, we have high confidence that minimal bias due to false negative or false positive detection occurred. The details and caveats of pyroCb detection are provided by Peterson et al. (2025), npj Climate and Atmos. Sci. (accepted).

3. **Clarification of the SALD product's origin and validation (Section 2.6)** It is not entirely clear whether the Stratospheric Aerosol Layer Detection (SALD) product, which is derived from OMPS-LP observations, is a locally developed dataset specifically for this study, or an existing product previously used and validated. If the latter, references should be provided; if the former, additional methodological details and validation steps would strengthen the study's reproducibility and robustness.

The 'enhanced aerosol layer' flag, supplied with the NASA OMPS-LP retrieval, is described by Taha et al. (2021). The SALD product is the same but with additional filtering applied to minimize false detections of stratospheric aerosol layers linked to e.g., high-altitude clouds and small-scale tropopause altitude variations. We added some details regarding SALD definition to the respective section (Sect. 2.6). The reproducibility of this data product should be straightforward.

4. **Missing explanation for lack of stratospheric intrusion during peak fire activity**
   While the manuscript clearly distinguishes between PyroCb- and WCB- driven events, it does not address why the period of most intense wildfire activity (June-July), when nearly all PyroCb events were recorded (Fig. 1B) and most of the fire energy was released (Fig. 1A), failed to produce significant stratospheric intrusions.

There is an emerging realization of the fact that there is limited correlation between the basic wildfire metrics (such as burned area, FRP or pyroCb count) – and the magnitude of stratospheric perturbation.

It is established by Peterson et al. (2025) that the preponderance of pyroCbs do not inject material explicitly into the lowermost stratosphere. It is reasonable to state that the evidence of the 2023 wildfire season is that despite the large number of pyroCbs, the number of measurable stratospheric injections was small. Conversely, Peterson et al. (2025) also show that one does not need a season with many pyroCbs to have a major stratospheric injection (e.g., 2017 PNE in Canada). The key to a significant stratospheric impact the right set of meteorological conditions to be present

at the same time as a significant heat flux from the fire. The fine details of the meteorological conditions and fire characteristics involved in major stratospheric injections is yet to be understood and this is where field measurements are required. A comprehensive field experiment dedicated to pyroCb is planned in 2026 within the NASA INSPYRE project.

Possible explanations might include:

a. Reduced intensity or frequency of WCB activity during June–July.

Climatologically, the WCB activity is lower during early Summer (Eckhardt et al., 2004)

b. A lower tropopause height during September–October, favoring stratospheric intrusion.

While the seasonal variation of tropopause altitude may be deemed an important factor from the general point of view, the seasonality of the most significant stratospheric perturbations over the last decade does not support this conjecture suggesting a complexity of the processes involved.

These hypotheses could be evaluated using available datasets, and other explanations may also be relevant. To aid such an analysis, it may be useful to:

- Extend Fig. 4's time frame to include May–July.

Unfortunately, the simulation output obtained using the current model configuration is only available for August – October 2023 period.

- Disaggregate Fig. 8A by month or split into May–July and August–October periods.

We believe that the altitude reach of aerosol perturbation month-by-month is readily inferable from Fig. 8b,d.

Without addressing this question, the interpretation of the results remains incomplete, as highlighted by the summary on lines 664–668, which implicitly raises the question of *why* this pattern occurred.

The following text was added into the respective paragraph in Sect. 3.7:

Peterson et al. (2025) establish that most pyroCbs do not inject material directly into the lowermost stratosphere. Evidence from the 2023 wildfire season supports this, showing that despite the large number of pyroCbs, only a few produced measurable stratospheric injections. Conversely, Peterson et al. (2025) also demonstrate that a season with relatively few pyroCbs can still yield a major injection, as in the 2017 PNE case. The critical factor is the coincidence of favourable meteorological conditions with a sufficiently intense heat flux from the fires. The precise combination of atmospheric dynamics and fire characteristics that enable such major pyeoCb-driven stratospheric injections remains poorly understood, underscoring the need for targeted field measurements.

The text in the last paragraph was modified as follows: "*In summary, the extreme 2023 Canadian wildfire season was very different from the previous record-breaking wildfire and pyroCb outbreaks such as PNE and ANYSO that produced long-lived SCVs* *that self-lofted to the middle stratosphere. PyroCb activity linked to the 2023 wildfires did not produce these self-lofting smoke plumes. However, the incessant fire activity May through September with a succession of WCB episodes during August – September period led to a massive amount of smoke pollution across the Northern Hemisphere extratropical tropopause layer."*

5. **Comparison of CO observations with model output (Section 3.5)**
   The analysis in Section 3.5 could be further strengthened by comparing the measured CO concentrations with predictions from the MOCAGE model (if available). Such a comparison would help assess consistency between observations and simulations and provide additional context for interpreting the results.

The simulated CO data are not available from this particular modeling experiment. The comparison between MOCAGE simulations and IAGOS CO observations is provided by Cussac et al. (2020). As far as the consistency between MOCAGE and observations (in terms of the plume pattern and altitude) involved in this study, this is demonstrated in Fig. 3 and Fig. 4. Another study in progress by Hu et al. will provide a detailed comparison of MOCAGE simulations and lidar observations.

6. **Inclusion of injected mass estimates for additional wildfire events (lines 650–658)**
   Since the authors have already compared their results to other wildfire events (e.g., in Australia), it would be informative to also include the estimated injected aerosol masses for these events, not only for the PNE event. This would provide a more complete comparative framework for evaluating the 2023 Canadian wildfire injections.

The text has been revised as follows:

Taking into account the factor of 2.2 underestimation of the ExTL AOD by OMPS-LP as compared to that of SAGE III, the injected masses scale to 0.07 – 0.13 Tg, which is comparable to the largest documented wildfire-induced perturbations, namely the 2009 Black Saturday event (0.05 – 0.1 Tg); the 2017 PNE event (0.1 - 0.3 Tg) and the 2019 ANYSO Phase 1 event (0.2 – 0.8 Tg) as estimated by Peterson et al. (2018; 2020).

Specific (Technical) Comments

1. **Spectral range classification** (lines 103–104 vs. lines 113–114)
   In lines 103–104, the 300–380 nm range is described as encompassing both "UV and visible spectral regions," whereas in lines 113–114, the 340– 380 nm range is referred to solely as "UV spectral bands." The authors should ensure consistent terminology and spectral classification throughout the manuscript.

The mention of visible spectral range is incorrect and has been removed.

2. **Reference formatting** (line 131)
   The reference to *Taha et al., 2021* appears with inconsistent font formatting. Please standardize to match the manuscript's reference style.

   Formatting fixed.

3. **Clarification of Fig. 2C reference** (Section 2.7, line 143)
   It is unclear why Fig. 2C is referenced here and what specific information it contributes to this section. Additionally, the relevance of the "16 km" value mentioned in this context should be explained.

   The reference was corrected (Fig. S10).

4. **Integration of data sources** (end of Section 2)
   After introducing all data sources, it would be beneficial to add a brief methodological statement summarizing how these datasets are integrated in the analysis. This would help readers understand the workflow and interconnections between the various observational and model products used.

   A subsection has been added:

   2.13 Integration of data sources

   In this study, pyroCb detections from the global inventory were combined with satellite observations from OMPS-NM, TROPOMI, and OMPS-LP to track smoke injection and transport. The stratospheric extinction profiles from OMPS-LP and SAGE III/ISS were used to constrain the large-scale aerosol perturbation. Ground-based lidar (LILAS, OHP) and radiosonde profiles provided high-resolution vertical structure, while IAGOS in situ aircraft data supplied CO and O3 measurements for characterization of plume chemical composition. These observational datasets were combined with fire emissions from GFAS and compared against MOCAGE chemistry-transport simulations (with MODIS AOD assimilation) to evaluate injection heights, aerosol loading, and plume dispersion. This integrated workflow provides a consistent observational–model framework for analyzing the evolution of wildfire smoke in the lower stratosphere.

5. **Justification for WCB diabatic heating statement** (lines 498–499)
   The statement that "the low concentration of aerosols in the WCB plumes limits the degree of internal heating and thereby does not enable diabatic self-lofting in the stratosphere" requires either a quantitative calculation or supporting reference to substantiate the claim.

   The following sentence has been added here: *Indeed, radiative transfer simulations by Ohneiser et al. (2023) showed that the lofting rate strongly depends on the smoke plume's AOD.*

6. **Potential missing context before line 518**

The paragraph beginning at line 518 appears to reference preceding material that is absent. Phrases such as "another CO enhancement…" and "1.5 hours later" clearly indicate continuity with earlier discussion. The authors should verify whether relevant preceding text has been inadvertently omitted.

There is indeed a large chunk of text missing, it has been recovered:

During the active wildfire season in 2023, May through September, the IAGOS flights covered a total travel distance of 4.3 million km at cruising altitudes within the outflow region of Canadian wildfires (40°N - 90°N, 130°W - 30°E), out of which 8244 km (0.19 %), that is ~34 hours of flight time, was spent in conditions with CO concentration exceeding +3 sigma limit (195 ppbv, computed from the ensemble of cruise data). The percentage of transatlantic IAGOS flights affected by enhanced CO concentration amounts to 0.19%, which is a factor of 3 higher than the 21-yr average percentage of 0.06% (Fig. S9).

Figure 6 shows two examples of transatlantic flights sampling intense smoke plumes from high-resolution Sentinel 5P TROPOMI AAI observations. The first case of 11 May 2023 corresponds to a flight from Montreal that crossed a 6-day old plume originating from the cluster pyroCb event in Alberta on 5 May (#1 in Table 1). The flight track across the high-AAI plume over Nova Scotia is shown in Fig. 6A, whereas the time series of GPS altitude, CO and O3 mixing ratio along the A-B flight segment are shown in Fig. 6B. Shortly after reaching the cruise altitudes and crossing the dynamical tropopause (2 PVU), the aircraft was exposed to high CO mixing ratios reaching 601±39 ppbv. The CO enhancements are correlated with substantial dips in ozone mixing ratio, depleted by a factor of 4 with respect to the extra-plume environment. The ozone depletion within the smoke plumes has been reported by Bernath et al. (2022); Solomon et al. (2023); Ohneiser et al. (2021) and can be associated with transport and/or chemical processes.