nature portfolio

Peer Review File

Behind the growing interest in high-intensity wildland fire-generated pyrocumulonimbus storms

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Web links to the author's journal account have been redacted from the decision letters as indicated to maintain confidentiality.

13th May 22

Dear Dr Fromm,

Your manuscript titled "Behind the growing interest in pyrocumulonimbus storms" has now been seen by our reviewers, whose comments appear below. In light of their advice I am delighted to say that we are happy, in principle, to publish a suitably revised version in Communications Earth & Environment under the open access CC BY license (Creative Commons Attribution v4.0 International License).

We therefore invite you to revise your Perspective article to address the remaining concerns of our reviewers. In particular, please carefully consider the suggestions for clarification and expansion from the reviewers; we would also like to draw your attention to a recent publication that you may want to include (Bernath et al. "Wildfire smoke destroys stratospheric ozone, Science, 2022 https://www.science.org/doi/abs/10.1126/science.abm5611).

At the same time we ask that you edit your manuscript to comply with our format requirements and to maximise the accessibility and therefore the impact of your work.

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We hope to hear from you within two weeks; please let us know if you need more time.

Best regards,

Heike Langenberg, PhD
Chief Editor
Communications Earth & Environment

On Twitter: @CommsEarth

REVIEWERS' COMMENTS:

Reviewer #1 (Remarks to the Author):

The paper is well written and contains an interesting (short and compact) overview (review) and summary about pyrocumulonimbus (pyroCb) clouds and their relevance and role in the climate systems.

I expect that such an article (with Mike Fromm as first author) will attract many scientists to read the paper and cite it later on. To my opinion it fits very well to Communications Earth & Environment.

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Final sentence in the second paragraph: The third study (Ohneiser et al., 2021) argued that self-lofted smoke polluted the stratosphere in the northen summer 2019 after the sulfate plume from the Raikoke volcano eruption had established a dominant, hemispheric presence.
This (..the dominant hemispheric presence) is misleading (not true) and must be rephrased!
There is a clear link between emitted SO2 and formed sulfate aerosol (within three months after the volcanic eruption and emission of the SO2 plumes into the stratosphere). This holds for recent

volcanic eruptions, e.g., for the volcanoes Sarychev (June 2009), Calbuco (April 2015), Raikoke (June 2019), and Hunga Tonga (January 2022). And keeping this clear relationship in mind, the maximum aerosol optical depth (AOD) of the Raikoke aerosol was 0.025 (at 500nm), and later on in October-November 2019 of the order of 0.015 at northern latitudes (e.g., during the northern summer, High Arctic).
Ohneiser et al. (2021) introduced the self-lifting or self lofting aspect/concept (an alternative way to pyroCb lifting) and reported UTLS (upper tropospheric and lower stratospheric) AODs of >0.25 (in the northern summer 2019) and later on during the MOSAiC expedition (October and November 2019) of 0.1 (for the stratospheric aerosol). And this AOD (one order of magnitude higher than the Raikoke-related AOD) was caused by smoke! and clearly not by Raikoke aerosol. So there must have been another aerosol source in the summer 2019, very clear! and that source were the huge Siberian fires. The smoke (AOD=0.1 in October 2019, Ohneiser et al., 2021) was clearly dominating (Raikoke AOD=0.015) and not the other way around.
Thus, please rephrase the sentence!

Section with title: How do pyroCBs alter our environment?

In the final paragraph: …the potential for a smoke plume to impact stratospheric chemistry is a frontier topic (54,62-64).

Please add the reference Ohneiser et al. 2021 (45) here as well! Ohneiser et al. (2021) were the first who pointed to a potential impact of wildfire smoke on ozone depletion (already in the available ACPD version published in February 2021). And this smoke-ozone aspect, presented in this paper, was then highlighted by Voosen (2021) in a small report in the Science Magazine in November 2021.

In the final paragraph at the end… If the circumstances are such that the residual pyroCb plume is in a position to be drawn to polar latitudes and thereby reside within the wintertime vortex, the possibility of a 'new' agent in the seasonal ozone-depletion mechanism would then exist.

Again, Ohneiser et al. (2021) (… regarding smoke-related ozone depletion over the High Arctic) … as well as Ohneiser et al. (2022) (… regarding smoke-related ozone depletion over Antarctica …, ACPD, acp-2021-1097, the revised version was recently accepted) … were the first who provided substantial information (measurements) to this research field (rather than preliminary simulations results as Yu et al. 2021 or just an idea about a potential impact of smoke on the polar ozone layers, Stone et al, 2022, or a hypothesis concerning ozone depletion at midlatitudes, Solomon et al, 2022, or mid-latitude observations by Santee et al., 2022, 38-54°N and °S only.) Ohneiser (2021, 2022) are the only papers explicitly dealing with the polar ozone layer and the smoke impact.

Figure 1. Can we be sure that the center panel shows a Cb rather than just a volcanic ash plume?
Figure 2. What is the data source or basis for Figure 2, please provide a reference. Yes, there is a trend, however, without 2021, would not be able to see that… So maybe, there is a tendency….. describes it better?

All in all, a very useful and well written manuscript. I enjoyed reading very much!

Reviewer #2 (Remarks to the Author):

Review of 'Behind the growing interest in pyrocumulonimbus storms' by Fromm et al.

The quiescent state of the background stratospheric aerosols is often perturbed by injections from two major sources, volcanic eruptions, and relatively recently recognized fire-driven thunderstorms or pyrocumulonimbus (pyroCb) events. In view of the growing interest amongst the scientific community regarding these lesser understood sources of stratospheric perturbation, the manuscript by Fromm et al. tries to review the current state of understanding regarding mainly two aspects of pyroCb: formation/development of the pyroCb itself and the impacts of pyroCb at the ground level as well as in the stratosphere. The authors further discussed the challenges and recommended steps to better understand the pyroCb science.

In my opinion, the manuscript provides a good review of the former part regarding the development of the pyroCb, and the transport pathway of the pyroCb emitted smoke up to the stratosphere. However, it lacks the same thoroughness when discussing the impacts of the pyroCb on the stratosphere and the modeling challenges in robustly estimating these impacts. I provide the following comments as the grounds for this assessment. Before recommending the publication of the article, I would encourage the authors to address the following concerns:

Comments:
1. Lines 151-155 and 160-164: This is with regards to the discussion on alternate pathways for the pyroCb-sourced smoke transport to the lower stratosphere. In the event of a recognized pyroCb signal, the authors mention primarily two pathways: either direct injection into the stratosphere or via diabatic self-lofting of aerosols across the tropopause boundary. However, the latter pathway is provided lesser weightage citing observational limitations of Torres et al. (2020) and de Laat et al. (2012)
Firstly, this discussion is incomplete without the mention of the detailed modeling analysis by Das et al. (2021), a part of which was also included in Torres et al. (2020). Das et al. (2021) clearly demonstrated using a global chemistry-climate model that even though the bulk of the pyroCb-emitted smoke mass (black and brown carbon particles) was injected just below the local tropopause (~12 km) during British Columbia pyroCb of 2017 (in the model), the bulk of the smoke was able to cross the tropopause barrier and continue their further ascent to the satellite-observed altitudes of ~20-22 km. However, for a sensitivity simulation with a similar model set-up but without the inclusion of aerosol-radiation coupling or the aerosol heating feedback in the model, the bulk of the smoke did not cross the tropopause boundary or ascent as high as the observed smoke altitudes.

Secondly, why do the two pathways have to be competing? They could also be complementary to each other. The convective pathway can inject the smoke plume to upper tropospheric levels, while the injected aerosol mass and absorption properties (and the associated heating) would determine whether the smoke crosses the tropopause barrier.

2. Smoke transport in the stratosphere and modeling challenges: There is a dedicated section about the transport pathway of the smoke from the ground to the stratospheric levels, but the article lacks emphasis on how important it is for the models to also simulate the smoke transport accurately after the injections. Only then the chemistry-coupled global models will be able to robustly estimate the aerosol radiative impact, as well as impacts on stratospheric chemistry where particles provide the necessary surface for the heterogeneous chemistry reactions. Further, there can be interactions with large-scale circulation features (like Asian summer monsoon anticyclone (ASMA) after Canadian pyroCb injections of 2017, Kloss et al. (2019)) that could impact the regional stratospheric

composition. This poses a unique modeling challenge because most climate models usually run in two modes: forecast mode, where model meteorology soon deviates from the real meteorology, but this mode allows for the aerosol heating feedback. The other mode is where the model meteorological fields are nudged or adjusted using reanalysis datasets to allow for a more realistic transport, but the aerosol heating feedback may not be appropriately translated in this case due to the forced adjustments to the analysis fields.

3. Lines 220-27: regarding pyroCb-caused perturbation to stratospheric chemistry. Firstly, I believe the striking findings of your references 62-64 deserve a few more sentences here to better explain the role of aerosols in perturbing the stratospheric chemistry in general, and the possible “ozone loss” mechanism. Moreover, the authors state that the great challenge is “discerning and tracking high-altitude pyroCb plumes as they age and spread to high latitudes.”, but the greater challenge really is to find the changes in either reaction rates or “unknown reaction mechanisms” that have led to the observed repartitioning of reactive chemical species. The pyrocb-emitted smoke particles will have different surface properties compared to the better-known volcanic-sourced sulfate particles (e.g., Murphy et al. (2021)) and cannot be treated the same way in the models. Therefore, it is imperative for more field campaigns/ in-situ instruments to measure the particle composition and mixing state of the pyroCb-emitted particles at these high altitudes and use lab studies to infer the "missing" chemistry.

References:

1. Das, S., Colarco, P. R., Oman, L. D., Taha, G., and Torres, O.: The long-term transport and radiative impacts of the 2017 British Columbia pyrocumulonimbus smoke aerosols in the stratosphere, Atmos. Chem. Phys., 21, 12069–12090, https://doi.org/10.5194/acp-21-12069-2021, 2021.

2. Kloss, C., Berthet, G., Sellitto, P., Ploeger, F., Bucci, S., Khaykin, S., Jégou, F., Taha, G., Thomason, L. W., Barret, B., Le Flochmoen, E., von Hobe, M., Bossolasco, A., Bègue, N., and Legras, B.: Transport of the 2017 Canadian wildfire plume to the tropics via the Asian monsoon circulation, Atmos. Chem. Phys., 19, 13547–13567, https://doi.org/10.5194/acp-19-13547-2019, 2019.

3. Murphy, D. M., Froyd, K. D., Bourgeois, I., Brock, C. A., Kupc, A., Peischl, J., Schill, G. P., Thompson, C. R., Williamson, C. J., and Yu, P.: Radiative and chemical implications of the size and composition of aerosol particles in the existing or modified global stratosphere, Atmos. Chem. Phys., 21, 8915–8932, https://doi.org/10.5194/acp-21-8915-2021, 2021.

Reviewer #3 (Remarks to the Author):

The article presents a general framework of PyroCb research state and PyroCb most important impacts at the ground level but with a special focus on the impacts in the aerosols’ transportation pathways in the stratosphere. The paper has a big focus in comparing the pathways these clouds suppose in comparison with other similar phenomena such as volcanoes. Importantly, the paper is one of the first in giving a quantitative value of PyroCb occurrence around the globe for a period of nine years. Finally, the paper ends with an insightful section about the challenges that the scientific community faces in order to better understand this phenomenon.
The study is certainly appropriate in the scope of Communications Earth & Environment. The use of

literature is appropriate and with up-to-date references. The writing style is modern and punchy for a perspective paper, which I consider appropriate. However, I have some concerns regarding mostly the way the ideas are presented, the quality of the figures and the clarity of some concepts. I suggest the authors approach these items to have a higher quality and impact paper.

Major concerns:
- Figures need to be enhanced. The authors should increase the quality and information provided in Figure 1, and enlarge the images. There are many good photos that can be used here. I suggest adding an image of the algorithm detection of a PyroCb (and using the same PyroCB in the true color image). The reader will appreciate a visual help on the methodology been used as the bases for this paper, and will also help to more more focus on the PyroCb phenomenon than on the comparison of the three types of clouds, as it is now the feeling from seeing only the figure (and it is not the case in the main text).
- Figure 2 should be also improved. I suggest adding the continent in which the PyroCbs originated, it can be really informative and novel for the paper. In the caption, include the source or a brief note on the methodology.
- It would be useful to insert a table which will summarize the different pathways, Including variables such as typologies, evidence, impacts, references…. This section is a bit blurred, and a table could be really helpful.
- The term "storm" is very widely and not concisely used in the paper, having a mix of utilizations, ex: L17 PyroCb cloud, L22: firestorm cloud, L8: special storm cloud, L21: PyroCb phenomenon… And this only at the first paragraph. L78: doesn't use storm, but L27 does. L31 you say that the term "firestorm" is more colloquial than scientific. Can you define why "storm" is used and defend why it should be always used by the scientific community? Please consider removing the word storm from titles and major descriptions if it is not well justified.
- I suggest adding more information about the transitions from PyroCu to PyroCbs in the section "What is a pyroCb storm?", mostly facing the atmospheric drivers of such transitions. This will help the reader to better understand the phenomenon and the implications on its study.
- From my point of view the current structure is not the most logical, and some of the concepts explained are not placed in the most logical section. I list them here:
• L108-117: this is a methodology/physics-based explanation. Although it is used to somehow explain the evolution of methods to detect these events, it should be included in the "What is a pyroCb storm?" section. In this section you should mainly explain the changes in detection and occurrences.
• L129-136: those are important challenges. Please move the challenges to the "What are the pyroCb science challenges?" section and keep here the trends insights.
• Have you considered moving the "How do pyroCbs alter our environment?" section prior to "How new…" and "Transport pathways…" sections? I understand that it is first important to know the phenomenon (section "What is…"), understand its impacts (section ""How do pyroCbs alter…" and section "Transport pathways…"), and then see the past trends. Finally, finish with challenges to the future.
Minor comments:
L11: A period is missing in the sentence.
L16: Add citation recent storms North America
L24: Add "In this paper…"
L29: What do you mean with selective regional and seasonal domains? Expand
L32-34: Please add references
L36-39: A mix of concepts are deployed here. A high intensity fire can also be a wind-driven fire. And

a wind-driven fire may end up developing a PyroCu if conditions are favorable. Plume dominated fires are indeed high intensity fires dominated by the weather conditions formed by the fire itself, usually linked to the high energy released during the burning process.
L42-43: Please add a reference. Are PyroCu related to faster spread?
L93: Please add a reference.
L96: PyroCb science was born is a weird affirmation here. Why? Were scientists talking about PyroCb in these investigations?
L147-149: Please explain this sentence better. I don't understand why if it is not a PyroCb, a pathway is related to burning biomass.
L147-157: Section difficult to follow, please consider rewriting or explaining in a different manner.
L187-189: Very Good point, crucial question.

Authors' note: Our replies, inserted below, are in red.

We thank the reviewers for the positive and critical feedback. We hope and expect that our replies and actions will be satisfactory.

Note: The revised manuscript has been reorganized per a reviewer suggestion. In addition, some references have been added and others removed. Hence, the numerical order in the revised manuscript is different throughout. Below, where we refer to a numbered reference, it applies to the original manuscript. We believe this will eliminate confusion.

REVIEWERS' COMMENTS:

Reviewer #1 (Remarks to the Author):

The paper is well written and contains an interesting (short and compact) overview (review) and summary about pyrocumulonimbus (pyroCb) clouds and their relevance and role in the climate systems.

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This (..the dominant hemispheric presence) is misleading (not true) and must be rephrased!
There is a clear link between emitted SO2 and formed sulfate aerosol (within three months after the volcanic eruption and emission of the SO2 plumes into the stratosphere). This holds

for recent volcanic eruptions, e.g., for the volcanoes Sarychev (June 2009), Calbuco (April 2015), Raikoke (June 2019), and Hunga Tonga (January 2022). And keeping this clear relationship in mind, the maximum aerosol optical depth (AOD) of the Raikoke aerosol was 0.025 (at 500nm), and later on in October-November 2019 of the order of 0.015 at northern latitudes (e.g., during the northern summer, High Arctic).
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Thus, please rephrase the sentence!

The sentence on which the reviewer focuses is a simple description of the temporal evolution of the primary stratospheric aerosol type in northern summer 2019. "**The third study[45] argued that self-lofted smoke polluted the stratosphere in northern summer 2019 after the sulfate plume from the Raikoke volcano eruption[47] had established a dominant, hemispheric presence[48-50].**" This is true regardless of the comparative sulfate versus smoke AOD. I.e. before the smoke, the predominant aerosol type was sulfate. We have replaced "dominant" with "predominant."

Section with title: How do pyroCBs alter our environment?

In the final paragraph: …the potential for a smoke plume to impact stratospheric chemistry is a frontier topic (54,62-64).

Please add the reference Ohneiser et al. 2021 (45) here as well! Ohneiser et al. (2021) were the first who pointed to a potential impact of wildfire smoke on ozone depletion (already in the available ACPD version published in February 2021). And this smoke-ozone aspect, presented in this paper, was then highlighted by Voosen (2021) in a small report in the Science Magazine in November 2021.
We now cite Ohneiser et al. (2021) in the context of recent literature on smoke-ozone chemistry.

In the final paragraph at the end… If the circumstances are such that the residual pyroCb plume is in a position to be drawn to polar latitudes and thereby reside within the wintertime vortex, the possibility of a 'new' agent in the seasonal ozone-depletion mechanism would then exist.

Again, Ohneiser et al. (2021) (… regarding smoke-related ozone depletion over the High Arctic) … as well as Ohneiser et al. (2022) (… regarding smoke-related ozone depletion over Antarctica …, ACPD, acp-2021-1097, the revised version was recently accepted) … were the first who provided substantial information (measurements) to this research field (rather than preliminary simulations results as Yu et al. 2021 or just an idea about a potential impact of smoke on the polar ozone layers, Stone et al, 2022, or a hypothesis concerning ozone depletion at midlatitudes, Solomon et al, 2022, or mid-latitude observations by Santee et al., 2022, 38-54°N and °S only.) Ohneiser (2021, 2022) are the only papers explicitly dealing with the polar ozone layer and the smoke impact.

We respectfully decline to attach any citations to this particular sentence. Thanks to Reviewer 1's suggestion, reference 45 has been added where other related references are called out in the discussion of smoke/ozone depletion. Ohneiser et al. (2022) report on aerosols measured at a sub-Antarctic extratropical location (53°S) and provide no proof that smoke measurements at that location were at any time inside the Antarctic polar vortex. Given the premise of the sentence in question, it stands without any citations given the open question as to smoke observations inside the isolated polar air mass.

Figure 1. Can we be sure that the center panel shows a Cb rather than just a volcanic ash plume?

We have replaced the volcanic Cb panel with a more convincing image, and describe it fully in the caption. We have also replaced the image in the pyroCb panel with an example supported by cited eyewitness account.

Figure 2. What is the data source or basis for Figure 2, please provide a reference. Yes, there is a trend, however, without 2021, would not be able to see that… So maybe, there is a tendency….. describes it better?
We revised the manuscript to mention that the data illustrated in Fig. 2 came from the ad hoc, analyst-in-the-loop activity described in the previous paragraph. This approach was discussed in Peterson et al. (2017), which we now cite.

The reviewer makes a good point about the term "trend." We removed this term from the caption.

All in all, a very useful and well written manuscript. I enjoyed reading very much!

Reviewer #2 (Remarks to the Author):

Review of ‘Behind the growing interest in pyrocumulonimbus storms’ by Fromm et al.

The quiescent state of the background stratospheric aerosols is often perturbed by injections from two major sources, volcanic eruptions, and relatively recently recognized fire-driven thunderstorms or pyrocumulonimbus (pyroCb) events. In view of the growing interest amongst the scientific community regarding these lesser understood sources of stratospheric perturbation, the manuscript by Fromm et al. tries to review the current state of understanding regarding mainly two aspects of pyroCb: formation/development of the pyroCb itself and the impacts of pyroCb at the ground level as well as in the stratosphere. The authors further discussed the challenges and recommended steps to better understand the pyroCb science.

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Comments:

1. Lines 151-155 and 160-164: This is with regards to the discussion on alternate pathways for the pyroCb-sourced smoke transport to the lower stratosphere. In the event of a recognized pyroCb signal, the authors mention primarily two pathways: either direct injection into the stratosphere or via diabatic self-lofting of aerosols across the tropopause boundary. However, the latter pathway is provided lesser weightage citing observational limitations of Torres et al. (2020) and de Laat et al. (2012)

Firstly, this discussion is incomplete without the mention of the detailed modeling analysis by Das et al. (2021), a part of which was also included in Torres et al. (2020). Das et al. (2021) clearly demonstrated using a global chemistry-climate model that even though the bulk of the pyroCb-emitted smoke mass (black and brown carbon particles) was injected just below the local tropopause (~12 km) during British Columbia pyroCb of 2017 (in the model), the bulk of the smoke was able to cross the tropopause barrier and continue their further ascent to the satellite-observed altitudes of ~20-22 km. However, for a sensitivity simulation with a similar model set-up but without the inclusion of aerosol-radiation coupling or the aerosol heating feedback in the model, the bulk of the smoke did not cross the tropopause boundary or ascent as high as the observed smoke altitudes.

We defer to the reviewer by citing Das et al. in the revised manuscript.

In defense of our presentation, we give primacy to observations as opposed to theoretical simulations. Das et al.'s contribution, over and above Torres et al., is in the theoretical realm. As we point out by citing Fromm et al. (2021), observations of nascent stratospheric smoke after the British Columbia 2017 pyroCb event describe a scenario that Torres et al. and Das et al. did not take into account (a considerable mass of smoke immediately post-pytoCb exceeding the tropopause by as much as 4 km). This revelation is identical to that which we point out in relation to Black Saturday and de Laat et al., i.e. theory needs to account for observations counter to self-lofting.

Secondly, why do the two pathways have to be competing? They could also be complementary to each other. The convective pathway can inject the smoke plume to upper tropospheric levels, while the injected aerosol mass and absorption properties (and the associated heating) would determine whether the smoke crosses the tropopause barrier.

We have reworded our argumentation in this section of the paper to acknowledge the possibility of multiple pathways and clarify our perspective on the status quo. Below we offer the reviewer a fuller explanation.

"Competing" may be somewhat provocative by suggesting an either/or choice. If we stipulate that the ultimate vertical endpoint of the pathway is manifest stratospheric smoke (and other biomass-burning emissions), the science status quo is that the pyroCb pathway alone has been proven observationally. The sole published example of the purported tropospheric pyroCb followed by diabatic stratospheric lofting, Torres et al. (2020), was complicated by observational revelations of Fromm et al. (2021). It is natural for pyroCb events to involve pyroconvective injections at a range of altitudes spanning the UTLS, a point also demonstrated purposefully by Fromm et al. (2021). Consequently, even stratospheric pyroCb events leave behind coexistent, massive, protracted tropospheric and stratospheric smoke. Observational proof for a complimentary blend of pathways leading to stratospheric smoke has yet to be unequivocally demonstrated. This is the rationale for our stated perspective that proof of alternate single or combined pathways requires antecedent stratospheric conditions devoid of smoke that arrived by means of the pyroCb.

2. Smoke transport in the stratosphere and modeling challenges: There is a dedicated section about the transport pathway of the smoke from the ground to the stratospheric levels, but the article lacks emphasis on how important it is for the models to also simulate the smoke transport accurately after the injections. Only then the chemistry-coupled global models will be able to robustly estimate the aerosol radiative impact, as well as impacts on stratospheric chemistry where particles provide the necessary surface for the heterogeneous chemistry reactions. Further, there can be interactions with large-scale circulation features (like Asian summer monsoon anticyclone (ASMA) after Canadian pyroCb injections of 2017, Kloss et al.

(2019)) that could impact the regional stratospheric composition. This poses a unique modeling challenge because most climate models usually run in two modes: forecast mode, where model meteorology soon deviates from the real meteorology, but this mode allows for the aerosol heating feedback. The other mode is where the model meteorological fields are nudged or adjusted using reanalysis datasets to allow for a more realistic transport, but the aerosol heating feedback may not be appropriately translated in this case due to the forced adjustments to the analysis fields.

We have added a brief statement regarding the modeling challenges. This is definitely an important topic, but since our focus is on the pyroCb storm, we hesitate to expand too greatly into theoretical pursuits.

3. Lines 220-27: regarding pyroCb-caused perturbation to stratospheric chemistry. Firstly, I believe the striking findings of your references 62-64 deserve a few more sentences here to better explain the role of aerosols in perturbing the stratospheric chemistry in general, and the possible “ozone loss” mechanism. Moreover, the authors state that the great challenge is “discerning and tracking high-altitude pyroCb plumes as they age and spread to high latitudes.”, but the greater challenge really is to find the changes in either reaction rates or “unknown reaction mechanisms” that have led to the observed repartitioning of reactive chemical species. The pyrocb-emitted smoke particles will have different surface properties compared to the better-known volcanic-sourced sulfate particles (e.g., Murphy et al. (2021)) and cannot be treated the same way in the models. Therefore, it is imperative for more field campaigns/ in-situ instruments to measure the particle
composition and mixing state of the pyroCb-emitted particles at these high altitudes and use lab studies to infer the "missing" chemistry.

We have added a statement to the final section of the paper, calling out specifically the need for additional measurements, in situ and remote, of the residual stratospheric pyroCb smoke plume.

References:

1. Das, S., Colarco, P. R., Oman, L. D., Taha, G., and Torres, O.: The long-term transport and radiative impacts of the 2017 British Columbia pyrocumulonimbus smoke aerosols in the stratosphere, Atmos. Chem. Phys., 21, 12069–12090, https://doi.org/10.5194/acp-21-12069-2021, 2021.

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Reviewer #3 (Remarks to the Author):

The article presents a general framework of PyroCb research state and PyroCb most important impacts at the ground level but with a special focus on the impacts in the aerosols' transportation pathways in the stratosphere. The paper has a big focus in comparing the pathways these clouds suppose in comparison with other similar phenomena such as volcanoes. Importantly, the paper is one of the first in giving a quantitative value of PyroCb occurrence around the globe for a period of nine years. Finally, the paper ends with an insightful section about the challenges that the scientific community faces in order to better understand this phenomenon.
The study is certainly appropriate in the scope of Communications Earth & Environment. The use of literature is appropriate and with up-to-date references. The writing style is modern and punchy for a perspective paper, which I consider appropriate. However, I have some concerns regarding mostly the way the ideas are presented, the quality of the figures and the clarity of some concepts. I suggest the authors approach these items to have a higher quality and impact paper.

Major concerns:
- Figures need to be enhanced. The authors should increase the quality and information provided in Figure 1, and enlarge the images. There are many good photos that can be used here. I suggest adding an image of the algorithm detection of a PyroCb (and using the same PyroCB in the true color image). The reader will appreciate a visual help on the methodology been used as the bases for this paper, and will also help to more more focus on the PyroCb phenomenon than on the comparison of the three types of clouds, as it is now the feeling from seeing only the figure (and it is not the case in the main text).

We have greatly improved Fig. 1. The image resolution is enhanced. Features are annotated. Fire hot-spot observations have been added to the pyroCb panel. To give the reader an insight into the workings of a pyroCb, the figure panel now shows a pyroCb that is accompanied in the caption with a link to professional eyewitness accounts of the exact visualized pyroCb storm. The eyewitnesses were entrapped by the advancing pyroCb. Maps and photographs accompany the testimonials.

- Figure 2 should be also improved. I suggest adding the continent in which the PyroCbs originated, it can be really informative and novel for the paper. In the caption, include the source or a brief note on the methodology.

We made several improvements to Fig. 2. There are data details accompanying each bar in the charts. A second panel shows a breakdown by geographical region. The text now contains some additional interpretation to go with the enhanced figure.

- It would be useful to insert a table which will summarize the different pathways, Including variables such as typologies, evidence, impacts, references…. This section is a bit blurred, and a table could be really helpful.

In lieu of a table, we have addressed the blurriness by rewording the paragraph. It now describes the pathway differences more clearly and accounts for the evidence of the "competing" pathways. We feel that a tabulation of the pathways is premature given the unverified nature of the non-pyroCb pathways.

- The term "storm" is very widely and not concisely used in the paper, having a mix of utilizations, ex: L17 PyroCb cloud, L22: firestorm cloud, L8: special storm cloud, L21: PyroCb phenomenon… And this only at the first paragraph. L78: doesn't use storm, but L27 does. L31 you say that the term "firestorm" is more colloquial than scientific. Can you define why "storm" is used and defend why it should be always used by the scientific community? Please consider removing the word storm from titles and major descriptions if it is not well justified.

We have made the terminology more precise. We clarify the usage of "storm" by referring to the AMS glossary, which has a definition for
"storm" that applies to atmospheric disturbances of various sorts and scales. We characterize the pyroCb "storm" as a coupled fire-atmospheric disturbance manifested by the ice-capped Cb-like cloud. We now distinguish the labeling of the pyroCb as a phenomenon and not simply a cloud type.

- I suggest adding more information about the transitions from PyroCu to PyroCbs in the section "What is a pyroCb storm?", mostly facing the atmospheric drivers of such transitions. This will help the reader to better understand the phenomenon and the implications on its study.

To the best of our knowledge and experience, there is a dearth of knowledge about such the pyroCu-to-pyroCb transition. But we acknowledge that it is an important knowledge deficit that needs addressing. We have added some text acknowledging the science question, discussing the knowledge status quo, and stating the need for additional research.

- From my point of view the current structure is not the most logical, and some of the concepts explained are not placed in the most logical section. I list them here:

• L108-117: this is a methodology/physics-based explanation. Although it is used to somehow explain the evolution of methods to detect these events, it should be included in the "What is a pyroCb storm?" section. In this section you should mainly explain the changes in detection and occurrences.

This is a reasonable suggestion. However, we feel that the answer to "how new is the pyroCb" is most compellingly told with the account of the technical revelations that simultaneously educated us on "what is a pyroCb" and why it was missed for many years into the satellite era. We took the suggestion to heart and revised the text to better reflect the overarching significance of the various mysterious satellite signals to answer the question about how new the pyroCb really is.

• L129-136: those are important challenges. Please move the challenges to the "What are the pyroCb science challenges?" section and keep here the trends insights.

Excellent insight and suggestion. This text was moved to the initial paragraph of the "Challenge" section.

• Have you considered moving the "How do pyroCbs alter our environment?" section prior to "How new…" and "Transport pathways…" sections? I understand that it is first important to know the phenomenon (section "What is…"), understand its impacts (section ""How do pyroCbs alter…" and section "Transport pathways…"), and then see the past trends. Finally, finish with challenges to the future.

Good idea. Done.

Minor comments:

L11: A period is missing in the sentence.

Fixed.

L16: Add citation recent storms North America

Done.

L24: Add "In this paper…"

Done.

L29: What do you mean with selective regional and seasonal domains? Expand

This text was removed, as part of a larger rewording.

L32-34: Please add references

This discussion has been revised.

L36-39: A mix of concepts are deployed here. A high intensity fire can also be a wind-driven fire. And a wind-driven fire may end up developing a PyroCu if conditions are favorable. Plume dominated fires are indeed high intensity fires dominated by the weather conditions formed by the fire itself, usually linked to the high energy released during the burning process.

We hope our revised discussion is acceptable. It’s not clear what needs to be changed.

L42-43: Please add a reference. Are PyroCu related to faster spread?

The key term in this sentence is “intuitive.” The pyroCu signals fire excitation, which can result from a variety of factors. We have replaced “intuitive” with “subjective” in the absence of conclusive, cited reports.

L93: Please add a reference.

Done.

L96: PyroCb science was born is a weird affirmation here. Why? Were scientists talking about PyroCb in these investigations?

This wording has been removed. The discussion has been revised accordingly.

L147-149: Please explain this sentence better. I don’t understand why if it is not a PyroCb, a pathway is related to burning biomass.

The sentence has been amended to: “**Various transport pathways to the UTLS are commonly invoked for unusually massive biomass-burning-emission plumes observed at such high altitudes.”**

L147-157: Section difficult to follow, please consider rewriting or explaining in a different manner.

We have reworded this paragraph for clarity.

L187-189: Very Good point, crucial question.