Author Comment to Referee #2

https://doi.org/10.5194/egusphere-2025-5609, 'Continental and marine source regions contributing to the outflow of the Asian summer monsoon anticyclone during the PHILEAS campaign in summer 2023' by B. Vogel et al.

We thank Referee #2 for the positive review and for further guidance on how to revise our manuscript. Our reply to the reviewer comments is listed in detail below. Questions and comments of the referee are shown in italics. Passages from the revised version of the manuscript are shown in blue.

Reviewer Comments on the Introduction (Sections 1 and 2)

General assessment

The Introduction (Sect. 1) and the campaign and instrumentation overview (Sect. 2) together provide a thorough and well-referenced foundation for the study. The authors successfully place the PHILEAS campaign in the context of the Asian Summer Monsoon Anticyclone (ASMA), associated transport pathways, and recent aircraft and balloon campaigns. Section 2, in particular, offers a detailed and technically sound description of the HALO measurements and demonstrates the high quality and breadth of the observational data set.

We thank Referee #2 for this positive comment. A detailed discussion on the reviewer's comments follows below.

Major comments

1. *Structure and narrative flow of the Introduction (Sect. 1): The Introduction is scientifically comprehensive but very dense, with long paragraphs covering multiple themes. Rather than adding subheadings, which may disrupt the flow of a standard ACP Introduction, the text would benefit from clearer thematic paragraph separation, for example:*

   – ASMA formation, vertical transport, and confinement within the anticyclone.

– Export pathways via filament shedding and eddies to the extratropics.
– The role of tropical cyclones (TCs) in modifying UTLS composition.
– Previous observational campaigns and the specific contribution of PHILEAS.

Such restructuring would improve readability and help guide the reader toward the study's main objectives.

In addition, a schematic summarizing transport pathways (South East Asia, Western Pacific) and the location of the campaigns would be helpful.

We revised the introduction according to the reviewer's advice to improve readability. Further we have prepared a schematic (as suggested) summarising the possible transport pathways into the outflow of the Asian summer monsoon anticyclone. This figure is added to the conclusions of our manuscript (Fig. 1 of this reply). We thank the reviewer for this very helpful suggestion.
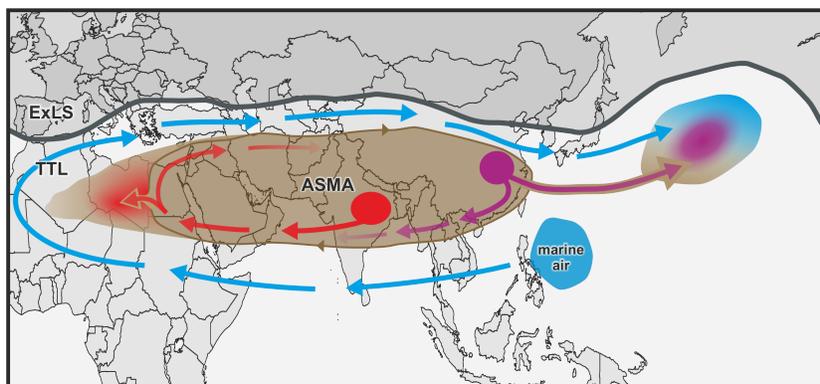
Figure 1: Schematic of the ASMA and its westward and eastward outflow (brownish arrows). Marine air from the western Pacific (blue) can be uplifted by tropical cyclones to altitudes of the ASMA and subsequently transported around the outer edge of the ASMA (blue arrows). Mixing of polluted air from inside the ASMA (brown) with marine air (blue) at its edge occurs at the eastern flank of the anticyclone when filaments are separated from the main anticyclone. Air masses measured in the eastward outflow of the ASMA are mainly from eastern China (purple) and the western Pacific (from the region of East Asian and Western North Pacific summer monsoons) in contrast to the western part that originates mainly from the Indian subcontinent (from the region of the Indian summer monsoon; red).

Also, 2023 was a very active Pyro Cb season in N. America (Peterson et al., 2025). It would be interesting to understand how it may have influenced PHLEAS measurements.

It is reported that the 2023 fire season set new records for total pyroCb activity, both regionally in Canada and worldwide (e.g. Peterson et al., 2025). Therefore, we agree with the reviewer that it is interesting to investigate whether pyrocumulonimbus (PyroCb) events that occurred in North America in 2023 had an impact on the PHILEAS measurements. The PHILEAS campaign was supported by Mike Fromm (US Naval Research Laboratory, Washington, DC, USA) with predictions of biomass-burning plumes, although forest fires were not one of the main objectives of the campaign. In the PHILEAS overview paper by Riese et al. (2025, in Tab. 1), an overview

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of all flights and their main objectives is given. Research flights F09 (28 August 2025) and F12 (7 September 2025) are related to forest fires. Further publications from the PHILEAS community focusing on the impact of biomass burning are in preparation (e.g. F. Ekinci et al., in preparation); however, including this topic in our work is beyond the scope of this study.

2. *Clearer articulation of novelty and the role of PHILEAS (Sect. 1): Several recent campaigns are mentioned (StratoClim, TACTS/ESMVal, WISE, ACCLIP), but the unique contribution of PHILEAS is not emphasized early enough. The authors are encouraged to more explicitly state what PHILEAS adds beyond these efforts. In particular, PHILEAS provides a valuable dual-flank perspective, sampling both:*

   - the western part of the ASMA and its westward outflow (Mediterranean region), and
   - the eastern flank and Pacific outflow (via flights from Alaska).

   Highlighting this earlier would strengthen the motivation for the study.

   We thank the reviewer for this very helpful comment and revised this paragraph according to the reviewer's advice as follows:

   The recent HALO campaign "Probing High Latitude Export of Air from the Asian Summer Monsoon" (PHILEAS) (Riese et al., 2025; Jesswein et al., 2025; Köllner et al., 2026) provided the first in situ observations in the northeastern Pacific region, where mixing of air from the ASMA into the extratropical lower stratosphere occurs (e.g. Vogel et al., 2016). The PHILEAS campaign was conducted from Oberpfaffenhofen, Germany, and Anchorage, Alaska, USA, during summer and early autumn 2023 and provides a valuable dual-flank perspective, sampling both the western part of the ASMA and its westward outflow (via flights from Germany to the Mediterranean region, Israel and Jordan) as well as its eastward outflow (via flights from Alaska to the northeastern Pacific region). More details are given in the campaign overview paper (Riese et al., 2025).

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3. *Instrument calibration and measurement stability (Sect. 2): Instrument accuracy and uncertainty are reported for FAIRO and UMAQS, which is helpful. To further support data quality in the UTLS, the authors are encouraged to briefly mention:*

   – the frequency of in-flight calibrations, and/or
   – observed instrumental stability or drift over the 20-flight campaign.

   This information could be added succinctly without expanding the section substantially.

   According to the reviewer's advice we added the following information to the manuscript.

   The conversion of the measured ERICA-AMS raw signal into mass concentrations involves several steps (for more details, see Eppers et al., 2025). The detection limit was determined for each measurement point by analysing the noise of the background measurement when a shutter in front of the ERICA-AMS ionisation region was closed (blocking ambient air and aerosol). Further, a de-trending method was applied (for more details, see Appel et al., 2022).

   The FISH instrument is calibrated every second flight and an instrument drift $< 1\%$ is estimated based on these regular calibrations for the PHILEAS campaign, which is included in the accuracy estimate.

   HAGAR-V uses two different in-flight calibration gases for a calibration measurement every fifth sample. The used gases were calibrated at the University of Frankfurt based on AGAGE-derived calibrations according to the SIO-14 (CH_2Cl_2) and the NOAA-03 (CH_2Br_2) scales. During PHILEAS the average measurement precision of CH_2Cl_2 and CH_2Br_2 was 1.3% and 2.3%, respectively.

4. *Rationale for trace gas selection (Sect. 2): While CH_2Cl_2 and CH_2Br_2 are highlighted as key species from HAGAR-V, the instrument measures a broader suite of tracers. A short sentence explaining why these short-lived*

halocarbons were prioritized (e.g., sensitivity to rapid uplift from polluted or marine boundary layers) would improve the scientific narrative and link the measurements more clearly to the study objectives. In this case, using CO as a tracer of deep convection over polluted areas would be useful.

The authors thank the reviewer for this comment and agree that this point requires further clarification. We have revised the HAGAR description as follows:

In addition, a mass spectrometer (MS) coupled to two GC channels by a two-position valve to alternately use the detector and thereby double the time resolution of the wide range of measured species is integrated (Lauther et al., 2022). In our study, CH_2Cl_2 and CH_2Br_2 are used as markers for anthropogenic sources – in particular from South Asia – and for natural oceanic sources – in particular for the western Pacific –, respectively.

Further publications from the HAGAR group are in preparation that make use of a broader suite of trace gases from the HAGAR measurements during PHILEAS (e.g. Strobel et al., in preparation; van Luijt et al., in preparation).

We agree that CO is a very good tracer of deep convection. We added CO measured by the UMAQS instrument along the flight tracks of research flights F02, F06, and F08, as shown in Figs. 2, 3 and 4 of this reply. The variability of CO and CH_4 (both measured by UMAQS) along the flight tracks is very similar; thus, CO confirms the variability already seen in CH_4, however CH_4 is the better marker for monsoon air. Therefore we think CO does not provide major additional value to the present paper. Because our paper is already very long and dense, we decided to not include CO as an additional trace gas in our analysis in order to avoid overloading our study with information.
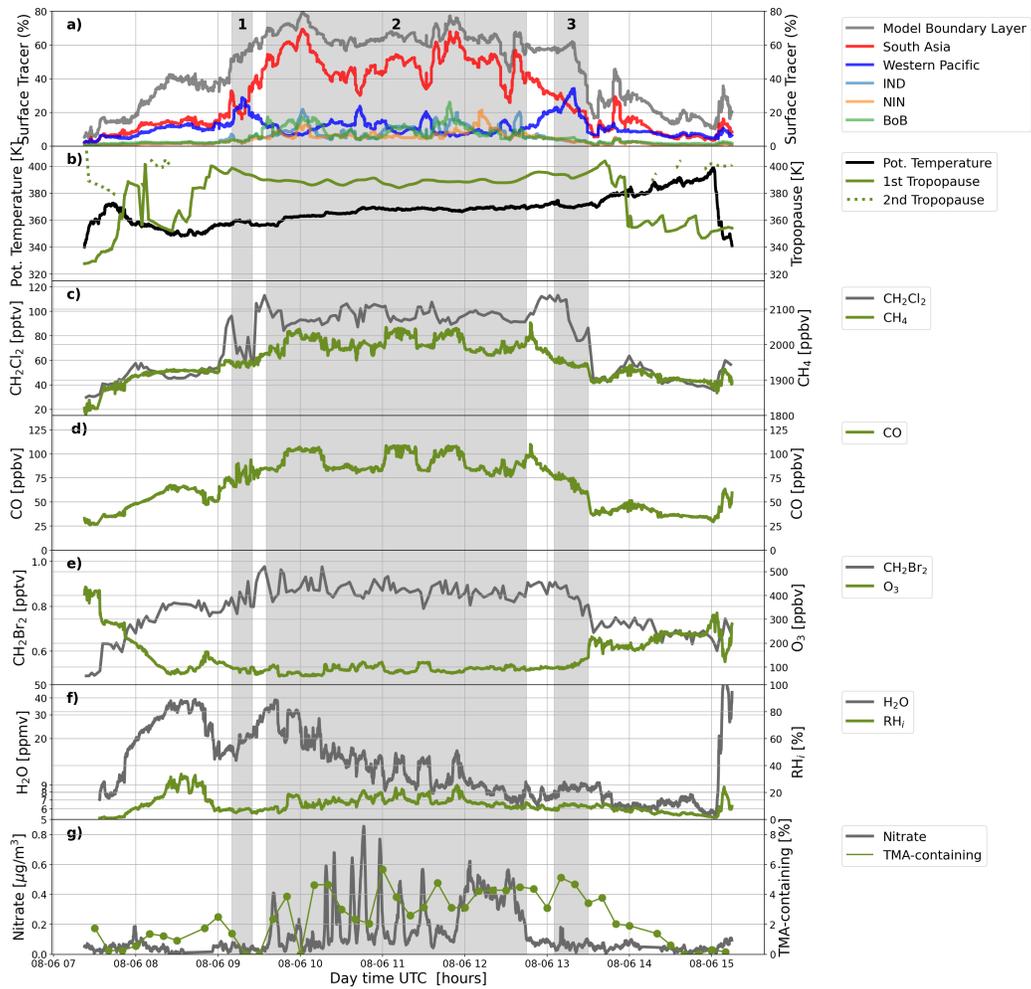
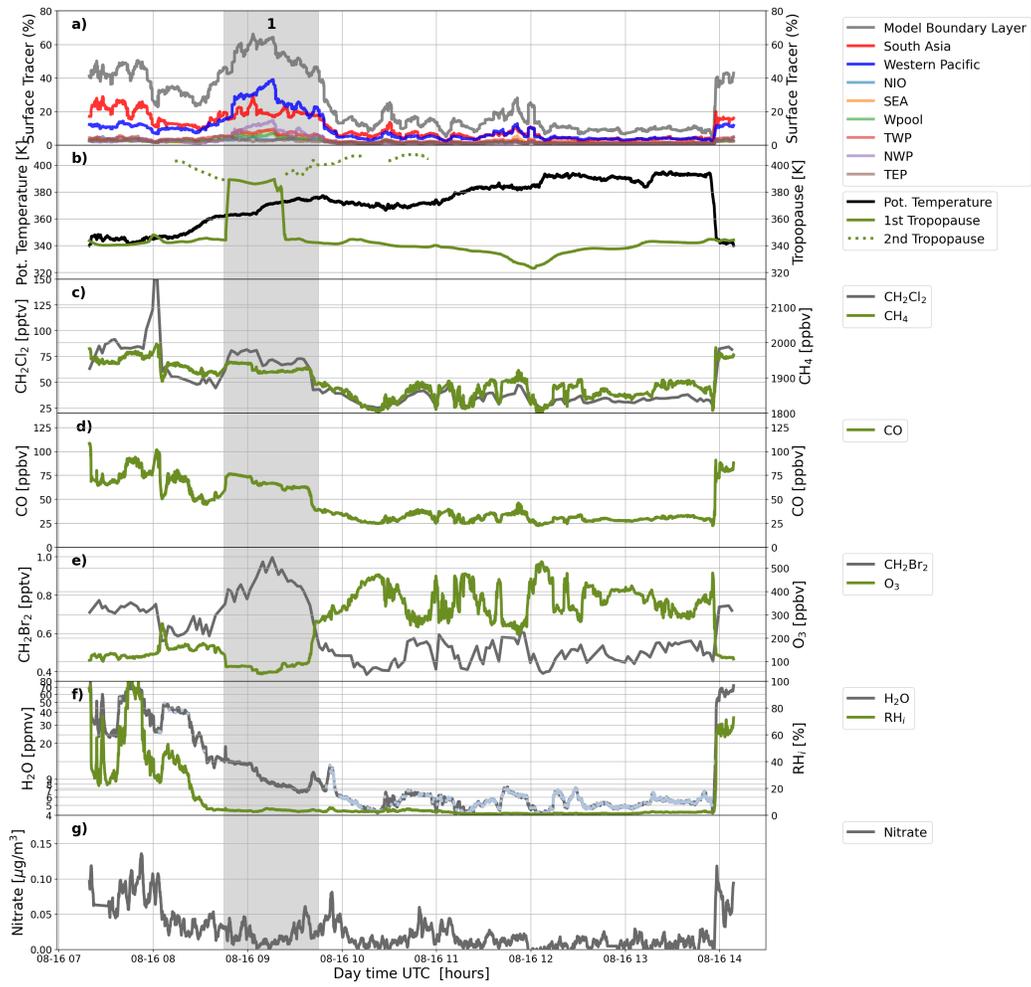Figure 2: As in Fig. 6 of the main paper, but with CO as additional trace gas.

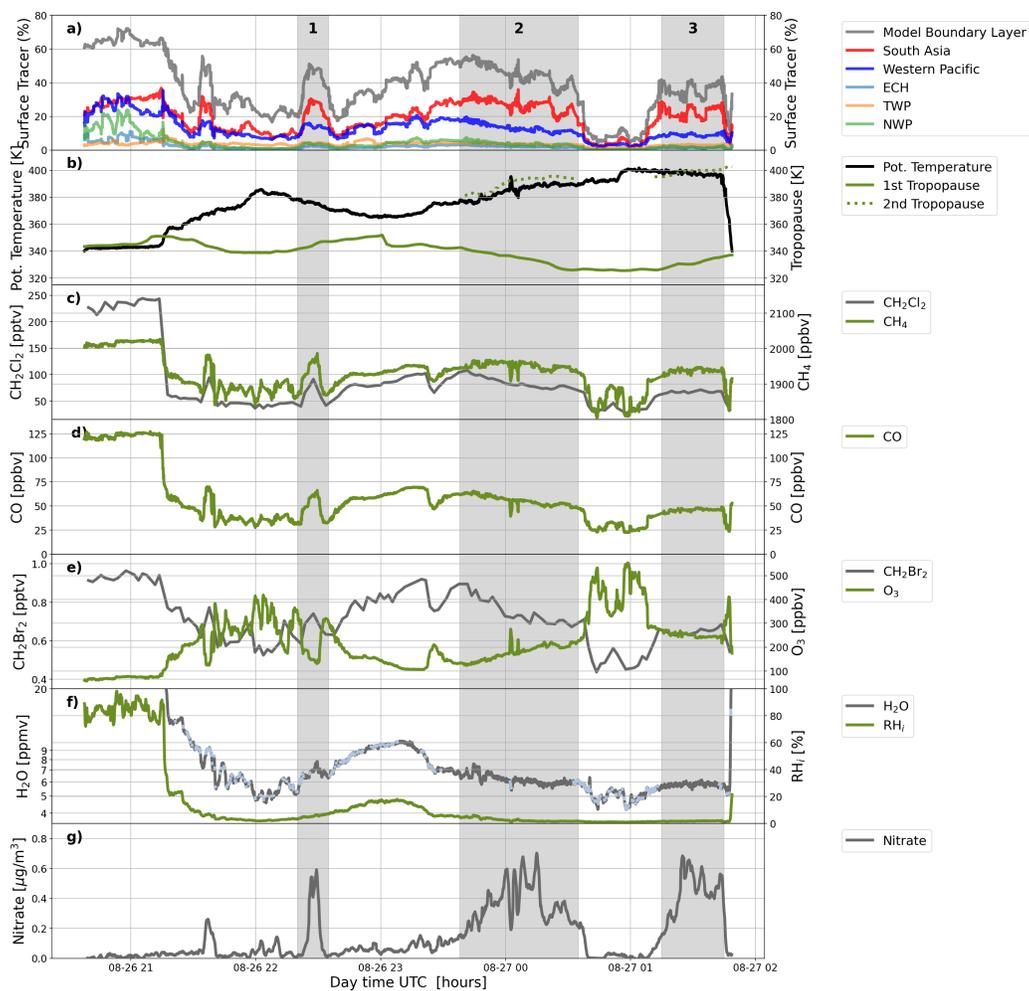Figure 3: As in Fig. 8 of the main paper, but with CO as additional trace gas.

Figure 4: As in Fig. 11 of the main paper, but with CO as additional trace gas.

5. *Scientific role of transfer flights (Sect. 2): Transfer flights (F07a, F07b, F19) are included in the data set, but their scientific role is not clearly stated. It would be useful to clarify whether these flights are used to characterize background extratropical UTLS or stratospheric conditions, thereby providing a reference for ASMA-influenced air masses.*

   One of the scientific objectives of the PHILEAS campaign was to analyse the large-scale impact of the Asian summer monsoon on the background state of the extratropical lower stratosphere, as discussed in the PHILEAS overview paper (Riese et al., 2025). During the transfer flights, measurements were conducted; however, scientific flight planning was very limited because of restrictions imposed by air traffic control authorities. Nevertheless, measurements obtained during the transfer flights can be used to infer the background state of the northern extratropical UTLS. Further scientific publications on this topic are in preparation (e.g. F. Ekinci et al.).

   For clarification, we revised the sentence as follows:

   Transfer flights between Oberpfaffenhofen and Anchorage (F07a, F07b, F19) can be used to infer the background state of the northern extratropical UTLS.

Minor comments and technical corrections

1. *typo (Sect. 1): 'into the the tropical tropopause layer' → remove the duplicated 'the.'*

   done

2. *Consistency (Line 31): Use 'westward' instead of 'westwards' to match 'eastward.'*

   done

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3. *Terminology (Line 45): Consider rephrasing 'ozone-poor and aerosol-poor marine air' as 'ozone- and aerosol-depleted marine air.'*

We prefer the terms 'ozone-poor' and 'aerosol-poor'. The term 'ozone-depleted' implies active chemical ozone loss, as occurs, for example, in the polar vortex. In our study, however, the low ozone mixing ratios result from the absence of ozone sources in tropospheric marine air.

4. *Line 47: You may add the influence of typhoons on cirrus cloud formation through stratospheric hydration and waves Pandit et al., 2024).*

Many thanks for the hint to Pandit et al, 2024; we were not aware of this study. We added the following text to the paper.

Similarly, ice crystals can be injected into the lower stratosphere by tropical cyclones, leading to hydration. The resulting moist plumes can subsequently be affected by the flow of the ASMA (Pandit et al., 2024).

5. *Acronym use (Sect. 1): After defining ASMA, please use the acronym consistently.*

We checked the entire manuscript and use the acronym ASMA consistently now.

6. *Conceptual clarity (Sect. 1): The term 'flushed' is well known but could be briefly linked to isentropic transport for physical clarity.*

We agree and revised the text as follows:

Consequently, during the Asian summer monsoon season, the northern extratropical lower stratosphere is flooded by isentropic transport – sometimes referred to as "flushing" (Hegglin and Shepherd, 2007; Müller et al., 2016) – with moist, polluted air originating from South Asia, which is among the most polluted and densely populated regions of the world.

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7. *Potential temperature phrasing (Sect. 2): Rephrase '~14.5 km (~1410 K)' as 'up to ~14.5 km, corresponding to potential temperatures up to ~410 K.'*

   done

8. *FISH correction (Sect. 2): Please indicate the typical magnitude of the gas-phase water correction in ice clouds to give context for measurement sensitivity.*

   The FISH data used in our study include a simple calculation of cloud ice water content, which assumes that the gas-phase water vapour in cloud conditions is at saturation with respect to ice. This applies when the FISH-enhanced total water exceeds the saturation mixing ratio. The inlet of the FISH instrument enhances the measured ice water content, depending on the true air speed of the aircraft, by about a factor of 10–15. As a result, a very strong increase in in-cloud total water vapour is typically observed. To determine the ice water content, we correct for this enhancement (Krämer and Afchine, 2004). This simplified approach was chosen because in-cloud observations are not the focus of our study. In any event gas-phase measurements of water vapour by FISH agree very well with the measurements of other hygrometers (e.g. Rollins et al., 2014; Singer et al., 2022).

9. *Figure 1 clarity (Sect. 2): Ensure the final figure is not overly cluttered and that time axes are clearly labeled in UTC, given the mix of Alaska and Germany flight segments.*

   We revised the x-axis of Fig. 1 of the main paper as shown in Fig. 5 of this reply.

10. *Line 50. A reference is missing.*

    We added the following reference.

    Hence, the rapid uplift by tropical cyclones generally transports air of marine origin to altitudes of the ASMA, but upward transport of polluted air

masses during landfall of tropical cyclones also occurs (e.g. Li et al., 2017).
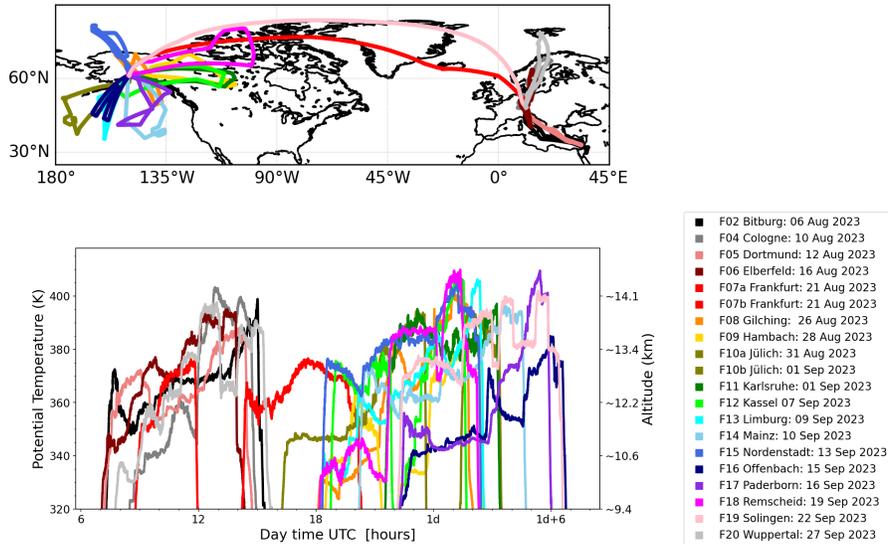
Figure 5: Regional map showing all HALO aircraft flight tracks over the Northern Hemisphere during the PHILEAS campaign 2023 (top). A total of 18 scientific flights (F02–F20; excluding the electromagnetic compatibility and turbulence calibration flights F01 and F03, and counting the double flights F07a/b and F10a/b as one flight each) were conducted between 6 August and 27 September 2023, departing from Oberpfaffenhofen (Germany) and Anchorage (Alaska). Maximum altitudes up to ∼14.5 km (∼410 K potential temperature) were reached. Research flights from Alaska were conducted during local daytime, which corresponds to nighttime in Coordinated Universal Time (UTC), and therefore often crossed the International Date Line, marked as 1 day (Alaska local time = UTC - 7 h, Germany local time = UTC + 2 h considering summer time).

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Reviewer comments on Section 3: Lagrangian transport simulations

General Comments:

The authors provide a robust description of the CLaMS model setup, the use of ERA5 reanalysis, and the implementation of surface-origin tracers. The distinction between the 3D Eulerian-Lagrangian simulations (including mixing) and the pure back- trajectory calculations is well-maintained. The use of specific tracer sums to define "South Asia" and "Western Pacific" origins is a powerful diagnostic for interpreting the PHILEAS measurements.

Thanks for these positive comments.

Major Comments:

1. *Resolved vs. Unresolved Convection: The authors explicitly state (Line 146) that no additional convective parameterization is used and that unresolved small-scale convection is not considered; in other words, tracer fractions represent a 'lower limit'. Given that the ASMA is driven by deep convection, the authors should briefly discuss the implications of this underestimation. Specifically, how might the omission of sub-grid scale convection affect the calculated 'age of air' or the timing of the "flushing" of the stratosphere?*

   We agree that the underestimation of unresolved small-scale convection and the the vertical transport of ERA5 could impact the absolute fractions of the surface–origin tracers. We revised the text as follows:

   The upward transport and convection in CLaMS (in both trajectory calculations and three-dimensional simulations) depend on the underlying reanalysis data (Li et al., 2020; Clemens et al., 2024; Vogel et al., 2024). For the use of high-resolution ERA5 data, no additional parametrisation for convection is applied in our simulations. Although an additional parametrisation for convection in CLaMS has been developed (Konopka et al., 2019, 2022), it is in its present form designed for use with down-sampled ERA5 data (with a $1° \times 1°$ horizontal resolution and a 6-hourly temporal resolution). This approach is a computing-time-saving alternative that is well suited for

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global, multi-annual CLaMS simulations. The representation of convection and tropical cyclones (e.g., typhoons) in ERA5 has substantially improved compared to its predecessor, ERA-Interim (e.g., Hoffmann et al., 2019; Li et al., 2020; Malakar et al., 2020; Clemens et al., 2024; Vogel et al., 2024), and represents the best data currently provided by ECMWF. However, unresolved small-scale convection in ERA5 represents a potential limitation of our simulations. Furthermore, vertical transport in the lower stratosphere in ERA5 has been found to be somewhat too slow (Ploeger et al., 2021; Vogel et al., 2024), which may affect air masses transported upward into the stratosphere and subsequently advected isentropically to higher latitudes.

2. *Definition of the 'South Asia' Tracer: The South Asia tracer (Line 169) includes a broad range of regions, including "Northern Africa (NAF)" and 'Near East (Neast)'. While the authors note these contribute only small fractions, the NAF region is often associated with mineral dust and different chemical signatures than the anthropogenic-heavy IND/ECH regions. A brief justification or a sensitivity note on why these regions are grouped into the "South Asia" monsoon proxy would be beneficial.*

We thank the reviewer for this comment and revised the text as follows for better clarification.

Our simulations show that the following surface–origin tracers contribute in general to the composition of the ASMA: Northern Indian Subcontinent (NIN), Indian Subcontinent (IND), Tibetan Plateau (TIB), Eastern China (ECH), Bay of Bengal (BoB), Northern Indian Ocean (NIO), as well as the Near East (Neast) and Northern Africa (NAF), with the latter two contributing only in small fractions to the composition of the ASMA. In the following, we use the sum of these surface–origin tracers as a marker for air originating from the ASMA and refer to it as the South Asia tracer (despite minor contributions from regions outside Asia).

3. *Dehydration Methodology (Section 3.2): The criteria for identifying dehydrated air masses (Lines 206-209) are quite specific (e.g., 80% of the time below the tropopause before H2Osat,ice,min). Please clarify the sensitivity of the results to the '80%' threshold. Additionally, the use of a simple*

minimum saturation mixing ratio (H2Osat,ice,min) is a first-order approximation. Does this approach account for the fact that ERA5 temperatures may have a cold/warm bias at the tropical tropopause, which significantly impacts H2Osat?

To calculate dehydration, the aim is to exclude trajectories originating in the stratosphere that are transported into the troposphere, but have only a very short residence time just below the tropopause. These trajectories do not count to the transport of water vapour from the troposphere to the stratosphere and therefore, they are filtered out using a certain threshold. Convectively uplifted trajectories are not impacted by this filtering method because only the time is considered before $H_2O_{sat,ice,min}$ will be reached.

We chose a value of 80% as threshold; a lower value would be more tolerant and a higher value would be more restrictive. Figure 6 in this reply shows the sensitivity of the time periods classified as dehydrated using thresholds of 70%, 80%, and 90% along the flight track of research flight F06. The time periods of dehydration along the flight track remain nearly the same, however the fractions of trajectories marked as dehydrated varies (16%, 10%, and 3%).

We agree with the reviewer that this is a simplified approach. Furthermore, as already noted by the reviewer, temperature biases (e.g., in ERA5) can influence the absolute value of $H2O_{sat}$ and thus, of course, also the dehydration marker. However, the present study does not use the value of $H2O_{gas}$ directly, but only in comparison with the total water FISH measurements as a criterion to assess whether an air mass could have experienced dehydration or not.

We revised the text in the main paper accordingly.

To estimate dehydration, the minimum of the water vapour saturation mixing ratio with respect to ice ($H_2O_{sat,ice,min}$) along the back-trajectories is calculated based on ERA5 temperatures and pressures. Dehydration is only relevant in a first approximation for air masses that are transported from the troposphere into the lower stratosphere. Therefore, tropopause heights along the trajectories are used to check whether the trajectories originate in the troposphere before reaching $H_2O_{sat,ice,min}$ and remain in the stratosphere afterwards.
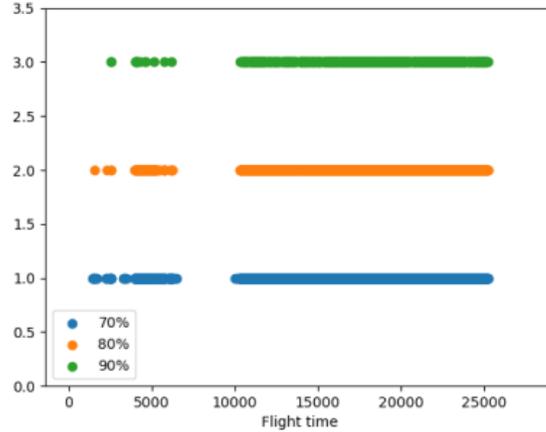
Figure 6: Sensitivity of the time periods classified as dehydrated using thresholds of 70%, 80%, and 90% along the flight track of research flight F06. The y-axis (values of 1, 2, and 3) is introduced solely to arrange the data within the plot. The time periods of dehydration along the flight track (x-axis) remain nearly the same.

Trajectories originating in the stratosphere and being transported into the troposphere, but with only a very short residence time just below the tropopause, are filtered out. Air parcels along the flight track are marked as dehydrated when the following criteria are fulfilled: trajectory (at least 80% of the time) is below the tropopause before reaching $H_2O_{sat,ice,min}$ and above afterwards, in addition FISH H_2O measurements (total water) should be greater equal $H_2O_{sat,ice,min}$ and to exclude measurements inside of clouds, FISH RH_i has to be lower than 90%. We determined a value of 80% as threshold because the time periods of dehydration using thresholds of 70%, 80%, and 90% along the flight tracks remain nearly the same.

4. *Mixing vs. Trajectory Consistency: The 3D simulations include "irreversible mixing applied every 24 h," whereas the back-trajectories (Section 3.2) appear to be purely advective (kinematic/diabatic). The authors should comment on how the lack of mixing in the backward trajectories might lead to discrepancies when compared to the 3D forward- modelled tracer distributions at the flight track.*

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Yes, we agree and added the following clarification to the manuscript.

CLaMS trajectory calculations consider only advective transport, neglecting mixing processes entirely. However, back-trajectory calculations are well suited to analyse the detailed transport pathway, transport time, and surface origin of air parcels and therefore provide added value compared to three-dimensional CLaMS simulations including irreversible mixing (as has been shown in previous publications, e.g. Vogel et al., 2019, 2023, 2024).

Minor Comments and Technical Corrections:

1. *Line 139 (Technical detail): The mention of MPI and shared memory storage is more of a technical implementation detail. While interesting, it could be shortened or moved to an appendix/supplement if space is a concern, as it doesn't directly affect the scientific interpretation.*

   Yes, we agree that MPI and shared memory storage are more of a technical implementation detail. However, the text related to this consists of only two sentences. We think that is not enough material for an appendix, therefore we decided to keep this text in the main paper.

2. *Line 183: The section title 'CLaMS back-trajectory calculations' might be more descriptive as 'Back-trajectory analysis and dehydration criteria'.*

   done

Reviewer Comments on Section 4: Results

1. *Threshold Definition: The text states 'measurements above about 360 K' (line 225), but Figure 3's bottom panel specifies '360K-420K'. This discrepancy risks ambiguity. The manuscript should explicitly align the text with the figure's precise range (e.g., 'measurements above 360 K, corresponding to the ASMA's upper convective outflow layer').*

We revised the text as follows to avoid any misunderstanding.

When focusing on measurements above the maximum level of convective outflow (i.e. 360 K) up to the maximum flight altitude (420 K), corresponding to the vertical extent of the ASMA (Brunamonti et al., 2018; Gettelman and de Forster, 2002), distinct source regions emerge....

2. *Cyclone Category Interpretation: The text claims cyclones (B) Talim, (C) Doksuri, (G) Saola, and (I) Haikui 'were all categorized as a typhoon' (line 235), but Figure 4's legend defines 'Typhoon' as category 5. Verify if all four cyclones are indeed category 5 (e.g., via JMA data) and correct the text if inconsistent.*

Tropical cyclones (C) Doksuri, (G) Saola, and (I) Haikui were classified as typhoons (category 5) and tropical cyclone (B) Talim reached a maximum intensity corresponding to a severe tropical storm (category 4) according to the data provided by the Japan Meteorological Agency under `https://www.jma.go.jp/jma/jma-eng/jma-center/rsmc-hp-pub-eg/besttrack.html`. This is consistent with our description in line 235: 'A strong local coincidence between the frequency distribution of air mass origins and cyclone tracks is found for cyclones (B) Talim, (C) Doksuri, (G) Saola and (I) Haikui north of the Philippines; the latter three were all categorised as a typhoon in this region (Fig. 4).'

Further, following the advice of Reviewer #1, we revised the legend for the tropical cyclones in Fig. 4 of the main paper for improved clarity. It now reads: Tropical Depression (TD), Tropical Storm (TS), Severe Tropical Storm (STS), Typhoon (TY), and Extra-tropical Cyclone (ETC).

3. *'overlayed' → "overlaid" (line 230).*

done

4. *'relations relations' → 'relations' (line 245).*

done

5. *Cyclone Impact Mechanism: The claim that cyclones 'rapidly uplift pol-luted boundary layer air' (line 237) requires supporting evidence. While Figure 4 shows spatial overlap, the manuscript should link cyclone timing to flight dates (e.g., 'Cyclone Khanun (D) impacted F08 on 26 July 2023, coinciding with elevated CH_2Cl_2 mixing ratios').*

Many thanks for this comment. The sentence in line 237 was intended as a general statement (see e.g. Li et al., 2017). We have removed this sentence in the revised version of the paper to avoid any misunderstanding.

6. *Reference Accuracy: 'Gettelman and de Forster, 2002' (line 223) likely refers to Gettelman and Forster (2002), a standard citation for convective outflow heights. Correct the reference to avoid confusion.*

Thanks for this comment. This is interesting. It seems that there is an issue in the spelling of the name of Piers Forster in the original publication. We use the name as written in the publication. `https://www.jstage.jst.go.jp/article/jmsj/80/4B/80_4B_911/_article`

7. *Tracer-Trace Gas Linkage: Section 4.2 states the goal is to 'demonstrate different chemical compositions' between source regions, but does not present results. Clarify whether tracer- tracer plots (e.g., CH_4 vs. CH_2Cl_2) are in-cluded in subsequent sections or if this section is purely methodological.*

We agree that is confusing. We revised the structure of Sect. 4.1 and 4.2.1 and merged them into one Sect. 4.2.

8. *The text notes 'frequent occurrence of strong tropical cyclones' (line 226) but does not quantify their contribution to total back-trajectory endpoints. Add a statistic (e.g., '30% of ASMA air masses originated from cyclone-impacted regions') to strengthen the claim.*

Many thanks for this comment. We agree that a further statistical analysis would be interesting. However, we believe that Fig. 4 of the main paper already demonstrates the impact of tropical cyclones.

9. *Line 255:* CH_4 *Threshold Ambiguity: The text states 'air masses with* CH_4 *mixing ratios exceeding a certain threshold', but does not explicitly define the threshold used in this study (e.g., 1850 ppbv vs. 1920 ppbv). While prior studies are cited, the manuscript should clarify whether a specific threshold was applied here or if the analysis focuses on all high-*CH_4 *air masses ($\geq$2000 ppbv, as implied in the text). This is critical for reproducibility.*

We revised the text as follows for better clarification.

In the PHILEAS campaign overview paper by Riese et al. (2025), air masses with CH_4 mixing ratios exceeding a threshold of 1850 ppbv (referring to Rolf et al. (2018)) were used as a proxy for monsoon-influenced air. In our study, no specific CH_4 threshold is applied, because in the outflow of the ASMA, mixing of monsoon air with surrounding air masses occurs, reducing the enhanced CH_4 mixing ratios associated with the ASMA.

10. *Line 271: The text describes 'three distinct branches' but does not explain how these branches were objectively identified (e.g., statistical clustering, visual inspection). A brief methodological note (e.g., 'branches were identified via k-means clustering with k=3') would strengthen the analysis.*

Many thanks for this comment. We revised the text as follows:

In this study, we use CH_4–CH_2Cl_2 relations as an indicator of monsoon-influenced air. The variability of CH_2Cl_2 over Asia helps to identify more local source regions within the continent. The CH_4–CH_2Cl_2 relation over all scientific PHILEAS flights (F02–F20) is shown in Figure 5. It demonstrates that the CH_4–CH_2Cl_2 relation is split into three distinct branches (clearly distinguishable by visual inspection) with varying CH_2Cl_2 mixing ratios at high CH_4 levels (greater than 2000 ppbv): up to 300 ppt of CH_2Cl_2 (branch 1 in Fig. 5), around 150 ppt (branch 2 in Fig. 5), and nearly 100 ppt

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11. *Line 287: The claim that region 4 'indicates marine air from the western Pacific' relies on* CH_2Cl_2 *matching 'northern hemispheric background values'. However, background* CH_2Cl_2 *could also originate from other regions (e.g., North America). The manuscript should:*

   – Cite specific background data to support this conclusion.

   – Acknowledge that CH_2Cl_2 *alone cannot definitively distinguish Western Pacific marine air without corroborating tracers (e.g.,* CO, O_3*).*

   We stated the text more precisely as follows:

   Large fractions of the Western Pacific tracer (up to 70%) are found for CH_4 mixing ratios of $\sim$1950 ppbv and CH_2Cl_2 mixing ratios of $\sim$50–60 ppt denoted as region 4 in Fig. 5. These low CH_2Cl_2 mixing ratios correspond to the northern hemispheric background from ground-based CH_2Cl_2 measurements during summer performed outside of Asia (`https://agage.eas.gatech.edu/data_archive/data_figures/monthly/pdf/CH2Cl2_mm.pdf`, last access: 27 Januar 2026; `https://gml.noaa.gov/hats/gases/CH2Cl2.html`, last access: 27 Januar 2026). Thus, air masses in region 4 are most likely marine air from the western Pacific, because both CH_4 and CH_2Cl_2 have only minor marine sources, and a large fraction – up to 70% – of the Western Pacific tracer is found.

12. *The text attributes high* CH_2Cl_2 *to South Asia but does not address potential contributions from other regions (e.g., Southeast Asia, East Asia). While Appendix A2 is referenced, the main text should briefly summarize key findings (e.g., 'branch 1 is dominated by eastern China, while branch 3 is linked to the Indian Subcontinent and Bay of Bengal').*

   Many thanks for this comment. We agree that this is an important point, and we have revised the text as follows:

Looking into the origin of the air masses using the South Asia and the Western Pacific tracer reveals that branches 1 and 2 have intermediate contributions from South Asia (reddish colours; fractions greater than 45%) mixed with lower fractions from the Western Pacific ($\sim$25-35%), except in the part of the relation in Fig. 5 (bottom left) denoted by 1b, where also substantial fractions from the Western Pacific ($\sim$40-50%) were found. Looking on single surface-origin tracers contributing the South Asia and Western Pacific tracer (Appendix A1; Fig. A1), our findings show that branch 1 is related to air mass origin in eastern China (ECH) and the Northern Western Pacific (NWP; in particular in region 1b), branch 2 in eastern China (ECH), Northern Indian Subcontinent (NIN) and the Tropical Western Pacific (TWP). Thus our findings confirm that enhanced CH_2Cl_2 in the UTLS can be attributed to sources in China (Feng et al., 2018; An et al., 2021; Pan et al., 2024; Jesswein et al., 2025).

In contrast, in branch 3 the fractions from South Asia are up to 70%, with minor contributions from the Western Pacific (tracer lower than 10%). Here the Indian Subcontinent (IND) and Bay of Bengal (BoB) are the main surface-origin tracers that contribute (Appendix A1; Fig. A1). CH_2Cl_2 mixing ratios in a similar range (up to about 140 ppt) were also measured during the StratoClim aircraft campaign over the Indian subcontinent, near the tropopause (Adcock et al., 2021).

13. *Line 288: The text states 'other parts of the world... have only a minor impact' but relies on Appendix A1 for evidence. The main text should summarize key findings (e.g., 'Appendix A1 confirms northern background and residual surface tracers contribute <5% to PHILEAS measurements').*

We agree with the reviewer and have added some quantitative details as follows:

To demonstrate that other parts of the world, besides South Asia and the Western Pacific, have only a minor impact on the PHILEAS measurements, the CH_4–CH_2Cl_2 relation is shown for surface–origin tracers representing the northern background (only relevant for local CH_4 emissions observed during take-off and landing of the HALO aircraft) that contributes with a

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fraction of ∼10% and the residual surface (mainly parts of the southern hemisphere) that has a negligibly impact (∼0%) on the PHILEAS flights in Appendix A1 (Fig. A1).

14. *Line 307: The text states the ASMA boundary is calculated using the Montgomery streamfunction (Kachula et al., 2025), but the figure caption specifies a Montgomery streamfunction value (MSF = 357.3 m^2 s^{-2}). Clarify whether the method relies on a fixed MSF threshold or a dynamic calculation. The 2025 reference is likely a typo (2024 or earlier); verify the correct citation.*

   Yes, we agree that this text needs some further clarifications. Therefore, we revised the text as follows:

   To indicate the edge of the ASMA, its horizontal boundary is calculated on selected isentropes using an optimised Montgomery streamfunction value based on the recently published method by Kachula et al. (2025). An advantage of this method is that it can be applied at any time scale, allowing the selection of individual days or specific hours. In Fig. 6, it is calculated on 370 K potential temperature for 6 August 2026 at noon using ERA5 reanalysis data.

   Figure caption of Fig. 6 is revised accordingly: To indicate the edge of the ASMA (indigo line), the boundary of the ASMA is calculated using the Montgomery streamfunction. An optimised Montgomery streamfunction value gives the ASMA boundary (MSF = 357.3 $\times 10^3$ $m^2 s^{-2}$) for 6 August 2023 at 12:00 and 370 K using ERA5 reanalysis data based on the method by Kachula et al. (2025).

   In the meantime, the paper by Kachula et al. (2025) has been published in ACP, and we have updated the citation accordingly.

15. *Line 313: The text claims 'opposite variations' between South Asia and Western Pacific tracers (Fig. 7), but Figure 7's color scale for 'Western Pacific' (blue) and 'South Asia' (red) shows overlapping trends in some*

segments. Quantify the degree of separation (e.g., correlation coefficients) to strengthen this claim.

We revised the text as follows:

Between approximately 9:15 and 13:30 UTC, the ASMA (Fig. 6 bottom, interval 2) the belt of air from the western Pacific was crossed by the research plane (Fig. 6 bottom, intervals 1 and 3). Qualitatively Fig. 7 shows that within this flight segment (intervals 1–3) the South Asia tracer and the Western Pacific tracer along the flight track exhibit opposite variations indicating that here the two different air masses are separated and not well mixed. This separation is caused by the transport barrier at the edge of the ASMA. Before and after this flight segment (intervals 1–3), fractions of the South Asia tracer are in general small $\sim 10\,\%$ (except at 13:50 where a small monsoon-influenced filament (outflow) was crossed).

We focus on a qualitative description of the variability of the South Asia and Western Pacific tracer along the flight path. Using correlation coefficients would imply that we have to select suitable time intervals over which the correlations are calculated. However, in several flight parts small–scale variability occurs. Therefore, here we restrict our analysis to a qualitative discussion.

16. *The text links TMA to 'marine sources and/or agricultural activities', but Figure 8f shows that TMA fractions are highest in interval 2 (South Asia-dominated) and 3 (Western Pacific- dominated). Explicitly test whether TMA correlates with both marine (CH_2Br_2) and anthropogenic (CH_2Cl_2) tracers to validate dual-source hypotheses.*

We revised the text as follows for better clarification.

Further, TMA-containing particles found in interval 2 indicate the influence from marine sources and/or sources in regions within rural areas with livestock farming and biomass burning such as in regions around the Bay of Bengal (West Bengal or Bangladesh). High mixing rations of CH_2Br_2 up

to ~ 0.9 ppt supports the hypothesis that natural oceanic sources or at least coastal regions contribute to air masses in interval 2. Interval 3 represents a mixture of air from South Asia and the Western Pacific; thus, both agricultural activities around the Bay of Bengal and marine sources in the Western Pacific are potential sources of TMA and CH_2Br_2.

17. *29. Line 362: The text asserts air masses in intervals 1 and 3 were 'uplifted by tropical cyclone Doksuri' (Fig. 9), but Figure 9's 'Cyclone Category' legend (bottom-right) shows only 2–3 categories. Clarify how cyclone intensity (e.g., typhoon vs. tropical storm) directly links to tracer uplift.*

Following the advice of Reviewer #1, we revised the legend for the tropical cyclones in Figs. 4, 9, 12 and 16 of the main paper for improved clarity (see above item no. 2). Further, we changed the colour for tropical cyclones and typhoon track for better clarification. Fig. 9 in the main paper clearly shows the coincidence of locations where air parcels were traced back from the flight track of research Flight F02 on 6 August 2023 to the model BL with the storm track of tropical cyclone Doksuri.

18. *The authors use 'particulate nitrate' as an ATAL indicator but do not quantify how nitrate mass concentrations in interval 2 (Fig. 8f) compare to established ATAL thresholds (e.g., ≥ 100 ng/m^3). Provide context for this metric.*

Unfortunately, we could not find any literature giving established fixed thresholds for nitrate within the Asian Tropopause Aerosol Layer (ATAL). However, if the reviewer is aware of any, we would appreciate being informed. We revised the text as follows:

Particulate nitrate is used as indicator for air from the Asian tropopause aerosol layer (ATAL) (e.g. Höpfner et al., 2019; Appel et al., 2022); mass concentrations of up to $0.8\,\mu\mathrm{g/m}^{-3}$ were found in time interval 2. During the StratoClim aircraft campaign over the Indian subcontinent in summer 2017, nitrate mass concentrations of up to $1\,\mu\mathrm{g/m}^{-3}$ were measured within the ASMA and the ATAL (Appel et al., 2022). Further, PHILEAS measurements show that outside the ASMA (and the ATAL), nitrate mass concentrations in UTLS aerosol are generally very low, often close to zero.

19. *The text references the ASMA boundary calculation using the Montgomery streamfunction (MSF = 357.0 m^2 s^{-2} at 370 K) in Figure 13's caption, but the main text does not explicitly define this threshold or its basis. Clarify whether this value is derived from a fixed climatological standard or dynamically optimized for the 2023 campaign.*

See above, authors comment to item no. 14. We used the method by Kachula et al. (2025).

20. *Line 410: The text states that 'South Asia and Western Pacific tracer fractions have similar values' in interval 1, but Figure 15a shows overlapping contributions from multiple regions (e.g., ECH, NWP, TWP). Specify the minimum fraction required to classify air as 'South Asia-dominated' or 'Western Pacific-dominated' and justify why 10% (as in Figure 15's caption) is significant.*

We apologise that there was an incorrect description in the text. We revised the text as follows:

Air masses measured in the eastward outflow of the ASMA originate mainly from East China (ECH) and the Western Pacific (NWP and TWP) (Figs. 14 and 15), in contrast to the western part of the ASMA, where air originates mainly from the Indian subcontinent (IND, NIN, BoB; Figs. 7 and 8). Within the filament measured on 26/27 August, somewhat higher fractions (by approximately a factor of two) of the South Asia tracer are generally found compared to the Western Pacific tracer (Fig. 14), in contrast to air in the western part of the ASMA (flight F02), where fractions of the South Asia tracer are higher by about a factor of seven (Fig. 7). During research flight F08, both tracers are positively correlated, in contrast to flight F02, where the two tracers are negatively correlated.

21. *Line 440: The text links interval 1–3 air to tropical cyclones (Talim, Doksuri, Khanun), but Figure 16's 'Cyclone Category' legend shows only 2–3 categories. Quantify how cyclone intensity (e.g., typhoon vs. tropical storm) correlates with tracer uplift (e.g., Fig. C4 in Appendix C) to strengthen*

causality.

See above, item no. 2 and 17.

22. *Line 418: The text states* CH_2Cl_2, CH_4, *and* CH_2Br_2 *'show a good overall agreement' with tracers, but Figure 15a–d shows asynchronous peaks (e.g.,* CH_2Br_2 *peaks at 21:40 while tracers peak at 22:00). Quantify correlations (e.g.,* R^2 *values) to validate the claim of 'good agreement'.*

To avoid any misunderstanding, we revised the text as follows:

The time series of the surface–origin tracers interpolated along the flight track of research flight F08 are also qualitatively compared with measurements of several chemical trace gases (Fig. 15). Both CH_2Cl_2, a marker for anthropogenic sources in Asia, and CH_4, a marker for monsoon-influenced air, are positively correlated with the South Asia tracer. After ∼22:00 UTC, the variability of CH_2Br_2, a marker for natural oceanic sources, follows that of the Western Pacific tracer. Before ∼22:00 UTC, at lower potential temperatures, however, the behaviour is more complex. O_3, a tracer for marine tropospheric and stratospheric air, also shows more complex behaviour in detail, but is generally negatively correlated with both the South Asia and the Western Pacific tracers. However, O_3 increases with potential temperature (interval 2), consistent with the increasing influence of stratospheric air.

As discussed above under item no. 15, here we focus on a qualitative description of the variability of the South Asia and Western Pacific tracer along the flight path.

23. *Line 427: The text suggests 'marine-sourced particles may have been removed via washout', but no evidence of precipitation along back-trajectories is provided.*

ERICA measurements show that enhanced levels of sodium chloride-, TMA-, or MSA-containing particles were detected during interval 1-3 (not shown), suggesting that marine-sourced particles may have been removed during

transport to potential temperature levels above 360 K, possibly through wash-out processes. In general, maritime-sourced particles can be transported upward by tropical cyclones, but also washout processes can occur. A detailed calculation of the precipitation along back-trajectories is beyond the scope of our study.

24. *Line 444: The phrase 'marine air form' contains a grammatical error ('form' should be 'from'). Correct such errors and replace repetitive terms (e.g., 'Western Pacific tracer' → 'WP tracer' after first use).*

The typo has been corrected. We prefer to use the term 'Western Pacific tracer' instead of 'WP tracer' for clarity.

25. *Figure 15's caption states 'flight segments are colour-coded in light-blue when dehydration is possible', but the text does not reference this. Explicitly link dehydration timing to the color-coding in the main text.*

We revised the main text according to the reviewers advise to better refer to Fig. 15.

Findings from back-trajectory calculations show that in intervals 1, 2 and 3 dehydration (flight segments that are shown in light–blue in Fig. 15e) does not occur (only for a minor number of trajectories), thus enhanced H_2O is found within the filament separated from the ASMA.

Reviewer Comments on Section 5: Conclusions

The Conclusions section provides a comprehensive synthesis of the PHILEAS campaign results and effectively highlights the combined roles of the Asian Summer Monsoon Anticyclone (ASMA) and tropical cyclones in shaping the chemical composition of the UTLS. The integration of HALO aircraft observations with CLaMS three-dimensional simulations and back-trajectory analyses is a clear strength of the study and supports many of the overarching interpretations. Nevertheless, several aspects of the Conclusions would benefit from clarification, moderation of claims, or additional contextualization to improve scientific rigor and

clarity.

1. *The Conclusions state that the South Asia tracer is a 'reliable proxy' for polluted air and that the Western Pacific tracer is a 'useful marker' for marine air uplifted by tropical cyclones. While these statements are plausible, they remain qualitative. It would strengthen the Conclusions if the authors briefly clarified what criteria underpin these characterizations (e.g., degree of correlation with measured tracers, consistency across flights, or robustness across potential temperature ranges). In addition, the manuscript refers to a background CH_2Cl_2 value of $\sim$50 pptv at tropopause levels; a short justification or reference for this background level would help contextualize the reported enhancements.*

   Yes, we agree with the reviewer that conclusions such as 'the South Asia tracer is a reliable proxy for polluted air and that the Western Pacific tracer is a useful marker for marine air' is a qualitative statement. We understand the wish to have a specific fixed value as an unambiguous criterion for monsoon or ASMA air. However, here we are focused on the edge and the outflow of the ASMA where mixing processes with air from other regions of the atmosphere (e.g. clean maritime air from the western Pacific or stratospheric air) occurs. Mixing of air from the ASMA into the northern extratropical UTLS is a multi-step process that yields a dilution of the air from the ASMA or the other way around an enrichment of the background air with pollutants from Asia over a time scale of weeks or months. The PHILEAS measurements just give a snapshot of these mixing processes. Depending on the extent of mixing between different air masses, the fractions of surface-origin tracers will vary.

   Further, we added in the conclusions the reference Adcock et al. (2021) for the CH_2Cl_2 value of $\sim$50 ppt at tropopause levels which was already discussed in Sect. 4.2.1.

2. *The reported dependence of CH_2Cl_2 mixing ratios on both altitude and source region is a key result. For example, the highest values (200–300 pptv) are found below the ASMA ($\leq$ 360 K), while lower values (100 pptv) dominate at ASMA altitudes ($\geq$ 360 K). The Conclusions would benefit from a short discussion of the physical or chemical processes that may explain*

this vertical structure, such as differences in convective efficiency, dilution during ascent, or chemical lifetime effects.

Many thanks for this comment. We revised the text following the reviewer's advice.

The highest CH_2Cl_2 mixing ratios $(200 - 300 \, ppt)$ are found from sources in China mixed with air from the Northern Western Pacific, however at altitudes below the ASMA ($\leq 360 \, K$) caused by both convection and strong CH_2Cl_2 sources in eastern China. Further, CLaMS simulations indicate, that CH_2Cl_2 mixing ratios of $\sim 150 \, ppt$ are a mixture of air from eastern China, Northern Indian Subcontinent and the Tropical Western Pacific; this is also valid for potential temperature levels below $360 \, K$. CH_2Cl_2 mixing ratios of $\sim 100 \, ppt$, at potential temperature levels of the ASMA ($\geq 360 \, K$) are associated with air masses mainly from the Indian Subcontinent and Bay of Bengal where CH_2Cl_2 sources can be assumed to be much lower than in China. In general, transport above the maximum convective outflow level ($\sim 360, K$) is much slower; thus, mixing with CH_2Cl_2-poor air within the ASMA becomes more important compared to air masses observed in the upper troposphere that are directly influenced by fast uplift of air from the main CH_2Cl_2 source regions in Asia. The short chemical lifetime of CH_2Cl_2 (~ 6 months) plays only a minor role compared to the time scales of mixing (dilution) within the ASMA.

3. *The Conclusions note the occurrence of ozone-poor air with enhanced CH_2Br_2 in the Western Pacific and attribute this to marine influence and possible cyclone-driven uplift. While this interpretation is reasonable, the relationship between ozone and CH_2Br_2 is not explicitly described. Indicating whether a clear (anti-)correlation is observed, even qualitatively, would strengthen the internal coherence of this argument.*

The negative correlation between ozone and CH_2Br_2 in marine-influenced air is discussed in detail in Sects. 4.3.2 and 4.3.3. We refine the sentence as follows for better clarification:

Measurements of ozone-poor and relatively enhanced CH_2Br_2 air that has

mostly natural oceanic sources indicate sources in the Western Pacific in agreement with CLaMS Western Pacific surface–origin tracer as well as back-trajectory calculations indicating possible impact of tropical cyclones (e.g., region 1 in Figs. 11 and 15).

4. *Enhanced trimethylamine (TMA) in the western part of the ASMA is attributed to agricultural sources in Northern India and the Bengal region. This is an interesting and potentially important finding, but the evidence supporting this attribution is not discussed in the Conclusions. A brief reference to prior studies or an explicit statement that this interpretation is tentative would make the conclusion more balanced.*

This issue is discussed in detail in Sect. 4.3.1. We revised the text following the reviewer's advice.

However, enhanced TMA was found in the western part of the ASMA during research flight F02, with an enhanced influence from northern India, in particular from West Bengal, Bangladesh, and the Bay of Bengal. Potentially large agricultural sources of TMA, as well as natural oceanic sources, may be associated with the measurements.

5. *The role of tropical cyclones in uplifting marine air into the UTLS is emphasized repeatedly and is central to the study's narrative. However, the Conclusions do not quantify the extent of this influence (e.g., the fraction of air masses at the ASMA edge linked to cyclone activity). Even an approximate or qualitative estimate would help readers assess the relative importance of cyclones compared to other transport pathways.*

Many thanks for this comment. We agree that a further statistical analysis would be interesting. However, we believe that Figs. 9, 12 and 16 of the main paper already demonstrate the impact of tropical cyclones to research flights (F02, F06 and F08).

6. *The manuscript highlights increasing intensity and duration of tropical cyclones in recent decades and suggests that direct injections of marine air*

into the UTLS will likely increase in the future. While this perspective is relevant, the connection between these long-term trends and the specific chemical impacts documented in this study could be articulated more explicitly to avoid the impression of speculation beyond the presented results.

We agree that combining the results of our study (the impact of tropical cyclones on the UTLS during PHILEAS) with the fact that the intensity and duration of tropical cyclones have increased in recent decades is somewhat speculative. However, this statement should be read as a forward-looking conclusion. The reviewer suggested in the last comment (see below) to add a forward-looking conclusion to our study.

7. *The Conclusions correctly point out that CH_2Br_2 is an ozone-depleting very short-lived substance and that its transport into the UTLS may have implications for stratospheric ozone. A brief indication of the potential magnitude or relevance of this effect (even in qualitative terms) would help place this result in a broader atmospheric chemistry context.*

Many thanks for this comment. We added the following explanation.

Bromine from very short lived substances such as CH_2Br_2, primarily from natural oceanic sources, contributes substantially to the stratospheric bromine loading and has a significant impact on modelled ozone and ozone trends in particular in the extratropical UTLS (Sinnhuber and Meul, 2015).

8. *Some redundancy is present, particularly regarding the role of tropical cyclones in uplifting marine air and influencing the ASMA edge. Condensing these statements could improve readability without weakening the main message.*

Many thanks for this comment. We agree and revised the conclusions accordingly.

Finally, the Conclusions do not explicitly address limitations of the study or outline directions for future research. Including a short statement on key uncertain-

ties (e.g., trajectory limitations, sensitivity to reanalysis data, or tracer interpretation) and possible next steps would provide a more balanced and forward-looking conclusion.

See above, comment to item no. 6.

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