Author Comment to Referee #3

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 #3 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.

General comments

1. *This paper provides a meticulous analysis of selected ASMA-related trace gas in situ measurements taken by the HALO research aircraft. It is very well written and of excellent scientific quality.*

   We thank Referee #3 for this positive assessment.

2. *Complementing previous campaigns, PHILEAS probed within the same season the western ASMA flank and also its eastern outflow. Three case studies are used to work out the differences between the respective measurements in detail. But are the selected cases really comparable? Measurements in the east probed a detached filament, i.e. ASMA outflow. The two western cases probed the edge and partly the interior of the ASMA, which may not be representative of the eastern ASMA outflow. Outflow via eddy shedding, for example, is likely to mix air masses across the transport barrier of the anticyclone.*

   Many thanks for this comment. We agree that the selected research flights addressed somewhat different situations; however all flights were influenced by tropical cyclones. And we further agree that we need to better motivate why we selected research flights F02, F06, and F08. For clarification, we have added the following text to the introduction of the revised manuscript.

We will show that in general the PHILEAS measurements are influenced by tropical cyclones from the western Pacific. Further, the chemical composition of monsoon-influenced air measured during PHILEAS varies strongly and depends on the geographic source region at the Earth's surface. We discuss three research flights (F02, F06, and F08) as case studies because, on the one hand, they sampled very different dynamical and geographic situations: the western part of the anticyclone, typhoon-influenced air within the westward outflow of the anticyclone, and the eastward outflow of the anticyclone. On the other hand, all three flights were influenced by marine air uplifted by tropical cyclones in the western Pacific, which contributes to the chemical composition of the air at the edge of the ASMA and its outflow. This results in mixing of polluted air from the Asian monsoon with marine air from tropical cyclones, particularly within eddies or filaments separated at the eastern flank of the anticyclone.

3. *The paper highlights the previously recognized interaction with tropical cyclones at the eastern ASMA flank (Vogel et al., 2014), which could lead to an asymmetry between eastern and western ASMA outflow. Gaining a general insight into the differences between the two types of outflow would require analyses that go beyond individual case studies. For instance, the extremely valuable ground truth provided by the case studies could be linked to satellite data or simulations, which provide longer temporal and wider spatial coverage, allowing for more general insights.*

We agree that the interaction of the ASMA with tropical cyclones at its eastern flank has already been discussed in several previous studies (e.g. Vogel et al., 2024; Li et al., 2017, 2020, 2023). In these studies, in situ trace gas measurements of CO, CH_4, H_2O, and O_3 obtained from aircraft or balloon observations were used. In addition, our study contains high-resolution in situ measurements of very short-lived substances such as CH_2Cl_2 and CH_2Br_2, as well as the chemical composition of aerosol particles (which were previously not available. This allows a better source attribution to maritime and continental sources to confirm our CLaMS model simulations using surface-origin tracers. This is a clear added value compared to previous publications to this topic.

For clarification, we added the following to the introduction of the revised

manuscript.

In addition, trace gas measurements and the chemical composition of particles are used to link the PHILEAS measurements to specific source regions such as marine (e.g. CH_2Br_2, marine-influenced particles) and continental sources (e.g. CH_2Cl_2, nitrate-containing particles) as well as monsoon air (e.g. CH_4). This allows a better source attribution combining model and measurement results.

We agree that it is also important to analyse a longer temporal and wider spatial coverage; however, this is not possible using only PHILEAS aircraft data, which are limited in both time and space (but provide very good spatial and temporal resolution). Such an analysis would constitute a completely different type of study, focusing on seasonal or climatological scales. This is something we may consider in future work, but can not be part of the present study focused on the PHILEAS measurements.

4. *Correlations between methane and dichloromethane are shown to be sensitive to different source regions, providing a valuable tool for studying ASMA-related transport. On the other hand, it would be worth discussing the different chemical compositions in the context of emission inventories for these trace gases, too.*

Many thanks that reviewer #3 appreciates the added values of the methane and dichloromethane correlations presented in our study. In addition with the surface-origin tracers from the CLaMS model, we can attribute enhanced dichloromethane and methane mixing ratios to certain source regions in Asia (e.g. eastern China and northern India) using high-resolution ERA5 reanalysis data with the best spatio-temporal resolution that is currently available from ECMWF.

In current chemistry-climate model simulations presented in Dubé et al. (2025), CH_2Cl_2 are constrained at the surface by annual mean observations in five latitude bands using surface values from NOAA `https://gml.noaa.gov/hats/gases/CH2Cl2.html`. In Claxton et al. (2019), three–dimensional chemical transport model simulations were performed to anal-

3

yse how chlorine perturbations vary with emission location of CH_2Cl_2. For this, CH_2Cl_2 abundance at the surface is modelled using 5 regions broadly correspond to major industrialised areas (Temperate North America, Europe, Temperate Latin America, Temperate Asia, and Tropical Asia) assuming a 1-Tg/year emission. Thus, to simulate chlorine including CH_2Cl_2, some rough assumptions had to be made. An et al. (2021) discussed the spatial distribution of CH_2Cl_2 emission in eastern China as shown in Fig. 1 of this reply highlighting China as an important source region that is not reflected either in Dubé et al. (2025) or in Claxton et al. (2019). However in our study, we do not present CLaMS simulations including chemistry, therefore any lower boundaries or emission inventories for CH_2Cl_2 will not be very helpful.

We revised our manuscript for better clarification as follows.

Dichloromethane (CH_2Cl_2), a chlorine-containing very short-lived halogenated substance (VSLS), originates mainly from anthropogenic sources – in particular from China and India (Feng et al., 2018; Say et al., 2019). An average annual increase of 13% in emissions of the industrially produced CH_2Cl_2 was reported for the time period between 2011 and 2019 – primarily from eastern China (An et al., 2021). Recent studies highlight the increasing influence of chlorine-containing VSLS such as CH_2Cl_2 that is not regulated by the Montreal Protocol on the stratospheric chlorine budget and therefore their possible role in ozone depletion (e.g. Hossaini et al., 2017; Claxton et al., 2019; Dubé et al., 2025). The coincidence of strong CH_2Cl_2 sources in Asia in particular in eastern China and the Asian summer monsoon that transport surface emissions from Asia very fast into the northern lower stratosphere, makes CH_2Cl_2 measurements in the ASMA and in its outflow very important.

Previous aircraft measurements already confirm that CH_2Cl_2 is enhanced over Asia. Over the Indian subcontinent CH_2Cl_2 mixing ratios up to $\sim$140 ppt were measured during the StratoClim aircraft campaign in 2017, a factor of more than two more than reported previously at the tropical tropopause ($\sim$50 ppt) (Adcock et al., 2021). During the ACCLIP aircraft campaign in 2022 record-breaking mixing ratios up to $\sim$ 600 ppt CH_2Cl_2 were measured at tropopause altitudes at the eastern edge of the ASMA (over Korea and Japan) (Pan et al., 2024). Export of air from the ASMA to the northern extratropical UTLS leads to enhanced CH_2Cl_2 mixing ratios over the Atlantic

Ocean and Northern Europe (Lauther et al., 2022) as well as in the Arctic (Laube et al., 2025).
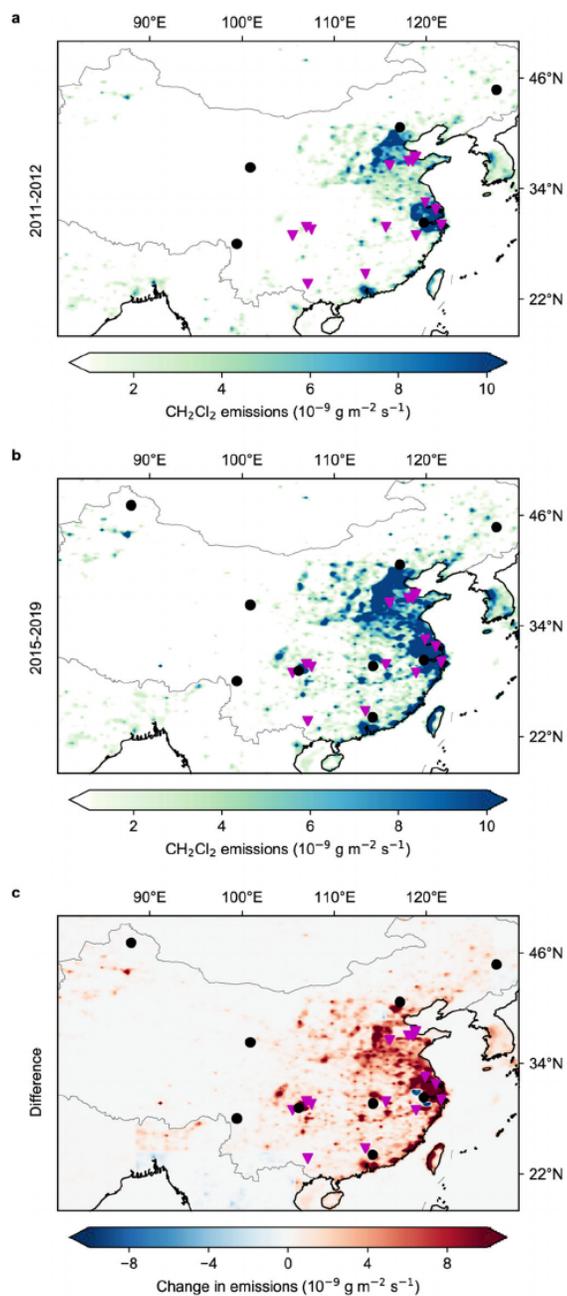
Fig. 3 Spatial distribution of CH$_2$Cl$_2$ emissions in Eastern Asia with focus on China. a The average mean emissions of CH$_2$Cl$_2$ in 2011–2012. **b** The average mean emissions of CH$_2$Cl$_2$ in 2015–2019. **c** The difference between **a** and **b**. The two time periods are divided by the rapid increase in emissions from China which occurred in 2012–2015. Black dots in the figures represent measurement sites active during that time period; pink triangles are the known chloromethanes factories in China. The spatial distribution for each year is shown in Supplementary Fig. 8. The difference between the spatial distribution of the mean top-down and a priori emission is shown in Supplementary Fig. 9.

Figure 1: From An et al. (2021, Fig. 3)

5. *The above aspects (eastern vs. western outflow, quantification of ASMA-cyclone interactions, CH2Cl2) are examples that could provide novel insights into ASMA-related processes or inventories. However, each would require analyses/quantification beyond the interpretation of the measurements. In the current draft I am having difficulty identifying the scientific focus. What do we learn about the ASMA that is not already known from previous studies, some of which are discussed in the introduction?*

Many thanks for this comment. We agree that we need to better underline the novelty of our study. Major novel points are further aspects of tropical cyclones and for example the added value of correlations between CH_4 and CH_2Cl_2. Therefore, revised the introduction accordingly (see above item no. 2).

6. *Nevertheless, the current draft provides a valuable, in-depth analysis. It is certainly worth publishing. Rather than revising the paper as suggested above: Why not making it a measurement report? Then it would likely require only minor revisions. Given the interesting dataset and the impressive, elaborate analyses, it even has the potential to be a highlight paper.*

We thank Reviewer #3 for the appreciation of our work and for recommending it as a potential highlight paper. We would be glad if the editor would think about that. A major component of our study is the back-trajectory analyses and global Lagrangian model simulations with CLaMS (the first global CLaMS simulation using high-resolution ERA5 reanalysis data) investigating the outflow of the ASMA (transport and mixing) and air-mass origins in Asia. According to ACP, *'Measurement reports are peer-reviewed publications that present substantial new results from measurements of atmospheric properties and processes from field and laboratory experiments. Analysis of the measurements may include model results and conclusions of* **more limited scope** *than in research articles.'* We do not consider a Measurement Report to be an appropriate format for our manuscript; CLaMS model simulations constitute an important part of the paper (see above) therefore, we submitted it as a Research Article. None of the other two reviewers raised any concerns regarding the manuscript type.

Specific comments

1. *L59: eastward − > westward?*

   'Eastward' is correct here. For better clarification, we revised the sentence as follows.

   The eastward outflow of the ASMA, transported along the subtropical jet toward North America and further downstream, was observed during two aircraft campaigns over Europe and the North Atlantic.

2. *L145: Is there an additional parameterisation for convection available (Konopka et al.), but was not used here? Or did Konopka et al. evaluate a setup without additional convection parameterisation? GENERAL: The representation of convection seems to be central for this study. If an alternative setup is available, a comparison would be warranted.*

   The authors thank the reviewer for this comment and agree that this point requires further clarification. 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 intended only 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 global, multi-annual CLaMS simulations. The representation of convection and tropical cyclones (e.g., typhoons) in ERA5 is 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; Vo-

8

gel et al., 2024), which may affect air masses transported upward into the stratosphere and subsequently advected isentropically to higher latitudes.

3. *L147: Is this necessarily a lower limit? Assume that a similar amount of instabilities is occurring in any resolution and that instabilities are removed by vertical motion: Small scale convection in high-res, larger scale in low-res. The locations and trajectories of the vertical exchange might differ, but not the amount of exchange. This means that the surface tracers are not necessarily at a lower limit. Instead, the low resolution imposes an additional uncertainty on the origin of the tracers. Comparisons to observed convection (clouds, lightning) might provide an idea of model performance in this context.*

   Yes, we agree and removed the expression 'lower limit' that was misleading (see revised text above item no. 2). In the past, several studies were performed to infer the different behaviour of CLaMS trajectories driven by ERA-Interim, ERA5 $1° \times 1°$ and high-resolution ERA5 reanalysis data in the vicinity of typhoons (more details see Li et al., 2020) in the western Pacific and of the Asian summer monsoon (more details see Clemens et al., 2024; Vogel et al., 2024).

4. *Since this aspect of vertical transport seems to be crucial for the study, a detailed discussion or even a dedicated evaluation of this aspect in the model seems to be warranted.*

   Yes, we agree that the vertical transport is crucial. In one of our previous studies, we have evaluated the vertical transport in CLaMS using high-resolution ERA5 reanalysis data using high-resolution in situ CO_2 measurements in the Asian summer monsoon 2017 up to $\sim$20 km altitude from the StratoClim aircraft campaign. Vogel et al. (2023) show that the Lagrangian transport in CLaMS using diabatic vertical velocities and driven by the European Centre for Medium-Range Weather Forecasts' new high-resolution reanalysis ERA5 is very well suited for CO_2 reconstruction. They show that spatio-temporal patterns of carbon dioxide on the Indian subcontinent driven by regional flux variations rapidly propagate to approximately 13 km with slower ascent above.

5. *L151: Are the gradients right for the right reasons? How sensitive are those evaluations to the representation of convective transport? See previous comment: An evaluation specifically for convection / the campaign period would increase confidence in the simulations.*

In Li et al. (2020), we performed a detailed analysis of the behaviour of CLaMS back-trajectories with respect to convection in tropical cyclones, as briefly explained below. Figure 2 (of the reply; same as Fig. 14 in Li et al. (2020)) displays the brightness temperature from the FY- 2G satellite with air parcels' locations at the corresponding time based on ERA-Interim diabatic trajectory calculations and ERA5 kinematic and diabatic trajectories. On 5 August, Naha was located at the northern edge of Typhoon Soudelor (Fig. 2a). On 6 August, air parcels from ERA5 kinematic and diabatic trajectory calculations were located above the centre of Soudelor (Fig. 2b). Some of the air parcels from the ERA-Interim diabatic trajectory calculations were still located at the edge of Typhoon Soudelor. Air parcels moved westward toward Kunming on 8 August (Fig. 2c), and the lowest brightness temperature is 190 K above Taiwan. On 9 August, air parcels arrived in Kunming under clear-sky conditions (Fig. 2d). Both the kinematic and the diabatic trajectory calculations using ERA5 data show much faster and stronger vertical transport than ERA-Interim primarily because of ERA5's better spatial and temporal resolution, which likely resolves convective events more accurately.

6. *L160: Back trajectories essentially serve the same purpose. Consider to add a few sentences explaining the purpose, the pros and cons of the two approaches. Forward simulations with source regions provide an impression of the air surrounding the measurements and they account for mixing. Do the back-trajectories also account for mixing?*

We thank the reviewer for this comment 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
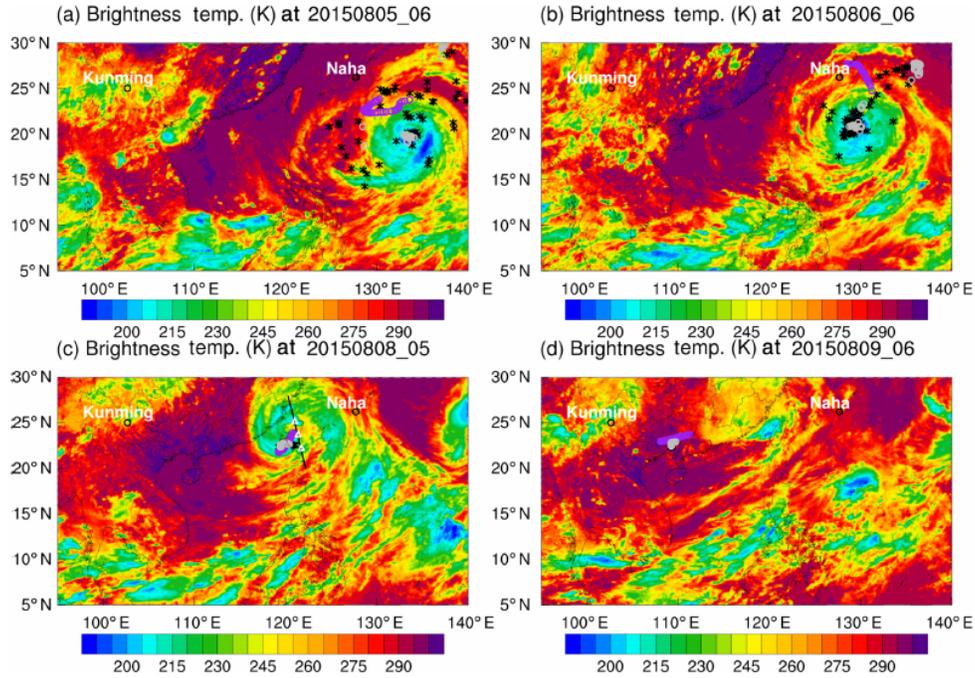
10

Figure 2: Brightness temperature from the FY-2G satellite on (a) 5 August, (b) 6 August, (c) 8 August, and (d) 9 August 2015 with backward trajectories (grey circles: ERA5 diabatic; black asterisk: ERA5 kinematic; purple circles: ERA-Interim diabatic) for air parcels started from balloon measurement in Kunming (China) in flight segments with low ozone and low water vapour as indicator for the impact of a tropical cyclone.

three-dimensional CLaMS simulations including irreversible mixing (this has been shown in previous publications, e.g. Vogel et al., 2019, 2023, 2024).

7. *L168: ASMA location and extent is very variable. Fixed surface regions neglect that. Why don't use some dynamic criterion (e.g. back-trajectories from the actual ASMA) to flag tracers as 'processed by ASMA'?*

To flag the air 'processed by ASMA' would be also a possibility to flag

11

monsoon-influenced air. However, we would like to attribute the measurements to different source regions in Asia, therefore we used the sum of different surface-origin tracers as marker for the ASMA in our study. For better clarification, we revised the text as follows.

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. 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 contributions from regions outside Asia). The regional surface-origin tracers can be used to link the measurements to sub-regions reflecting the influence of the South Asian monsoon (Indian subcontinent) or the East Asian monsoon (eastern China) (Smith et al., 2025; Pan et al., 2024, 2025).

8. *L225: How is that convection represented in ERA5?*

   This sentence was intended as a general statement. To avoid any misunderstanding, we have removed it.

9. *L233: Consider to evaluate/discuss the representation of cyclones in ERA5 for cases or regions relevant in this study.*

   The representation of convection and cyclones in ERA5 is already discussed elsewhere (e.g., Hoffmann et al., 2019; Li et al., 2020; Malakar et al., 2020; Clemens et al., 2024; Vogel et al., 2024). These papers are cited in our manuscript (see item no. 2 above).

10. *L255: 'Air masses ... monsoon region.' − > Consider to either provide some values (and references), or to omit the sentence.*

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

In the PHILEAS campaign overview paper Riese et al. (2025), air masses with CH_4 mixing ratios exceeding a threshold of 1850 ppbv (referring to Rolf et al. (2018)) was used as a proxy for monsoon-influenced air. In our study, no specific 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.

See also general comment item 4 above.

11. *L261-L269: The collection of facts about CH2Cl2 is somewhat inconsistent: Sources vs emission changes vs mixing ratios. How about showing or describing a snapshot of an emission inventory (if available)?*

A detailed comment on that issue can be found above (General comments; item no. 4).
In general, reliable, however detailed emission inventories for CH_2Cl_2 are not available.

12. *L296: Branch 3 has lowest CH2Cl2. Is this consistent with the main source in South Asia (as indicated in L262)?*

We revised the text for better clarification as follows.

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. A2). CH_2Cl_2 mixing ratios in a similar range (up to around 140 ppt) were also measured during the StratoClim aircraft campaign over the Indian subcontinent, near the tropopause (Adcock et al., 2021).

13. *L315: Consider to colour code the flight altitude in terms of potential temperature to indicate how it relates to the chosen isentropic level. A panel zoomed on the flight path might help visibility. In such detailed panel for the flight track you might also indicate the intervals used in figs 8, 11, 15.*

We agree that an additional panel zoomed on the flight track and indicating the intervals shown in Figs. 8, 11 and 15 is useful. We have added such figures to the revised version of our manuscript as shown in Figs. 3, 4 and 5 of this reply.
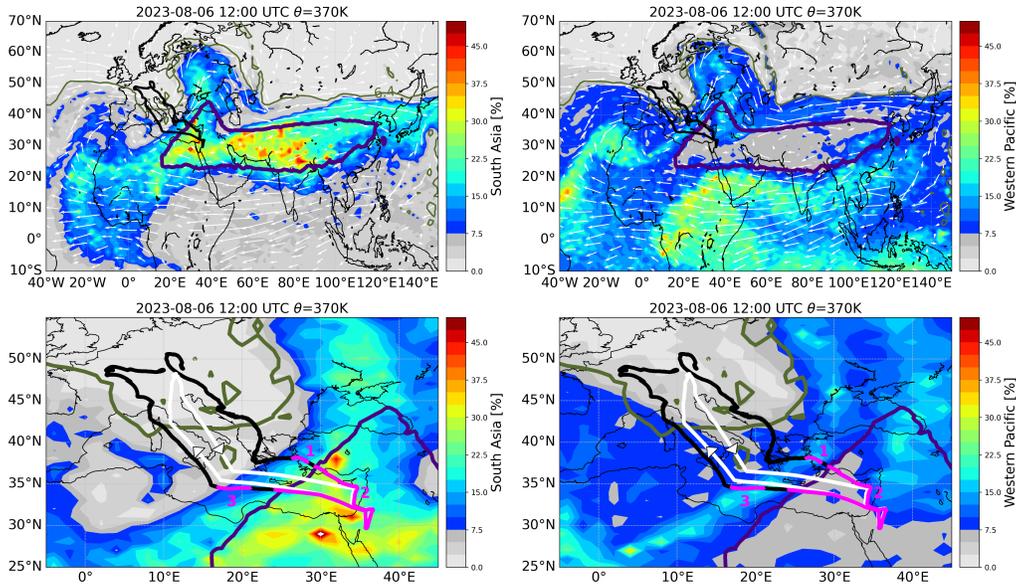
Figure 3: Research flight F02 on 6 August 2023 conducted from Oberpfaffen-hofen, Germany, to the Mediterranean area intruding into the western part of the ASMA (South Asia surface–origin tracer at 370 K, 12:00 UTC, left). The entire anticyclone (top) as well as a zoom to the flight area (bottom) are shown. A belt of air from the western Pacific is found around the outer edge of the ASMA (Western Pacific surface–origin tracer at 370 K, 12:00 UTC, right). The surface–origin tracer distributions are based on a CLaMS simulation driven by ERA5. To align the flight tracks with the synoptic CLaMS model output at 12:00 UTC, the actual flight positions (white line) were extrapolated to 12:00 UTC positions using forward and backward CLaMS trajectories to calculate the synoptic HALO flight track (black line). 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 = 357.3×10^3 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). The climatological isentropic transport barrier (PV = 6.4 PVU) derived by Kunz et al. (2015) for the Northern Hemisphere at 370 K during summer indicates the barrier between the tropical tropopause layer and the extra-tropical lower stratosphere (olive line). Further, horizontal winds from ERA5 are indicated by white arrows. Time intervals 1–3 shown in Fig. 8 are marked in magenta.
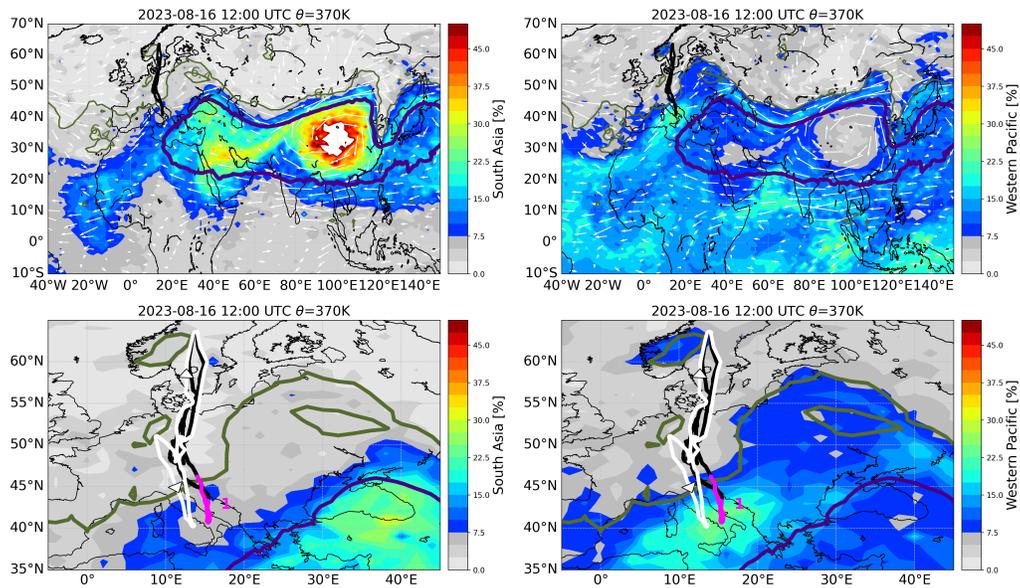
Figure 4: As in Fig. 3 but for research flight F06 on 16 August 2023 conducted from Oberpfaffenhofen, Germany, to the Mediterranean region (towards southern Italy). Research flight F06 reaches the outer edge of the ASMA (South Asia surface–origin tracer at 370 K, 12:00 UTC, left), which is dominated by air from the western Pacific (Western Pacific surface–origin tracer at 370 K, 12:00 UTC, right). The ASMA boundary (indigo line) is given by MSF = 356.6 $\times 10^3$ m^{2}s^{-2} for 16 August 2023 at 12:00 UTC and 370 K. Time interval 1 shown in Fig. 11 is marked in magenta.
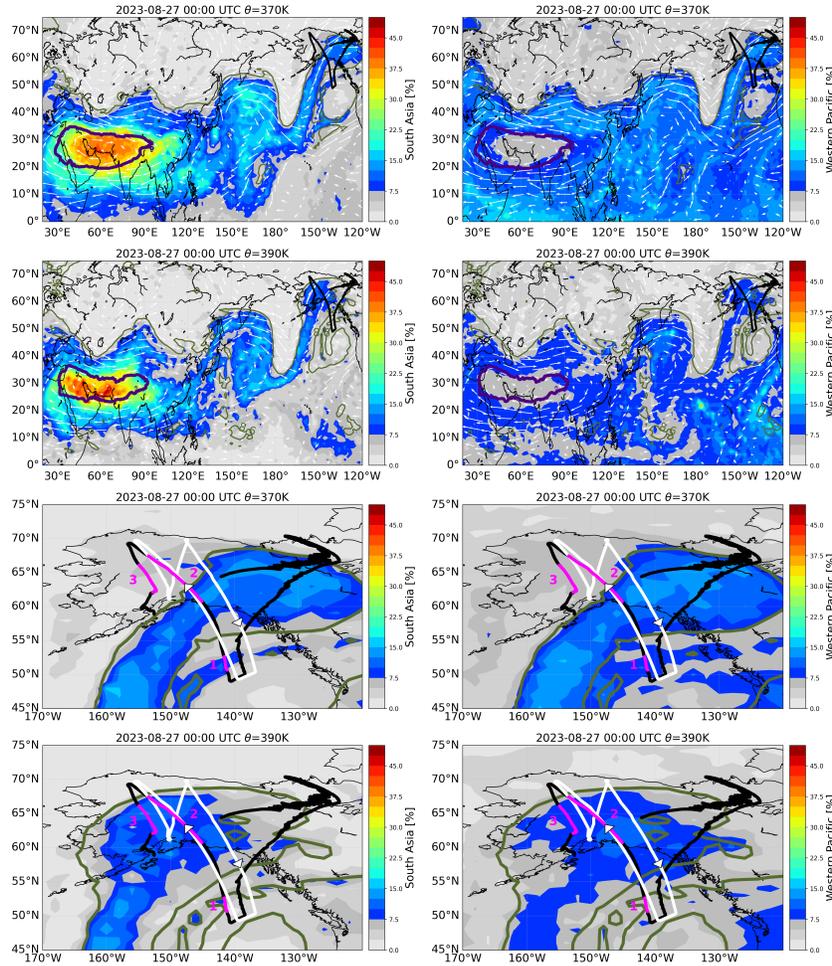
Figure 5: As in Fig. 3 but for research flight F08 on 26-27 August 2023 conducted from Anchorage probing a filament over Alaska separated from the ASMA (South Asia surface–origin tracer at 370 K and at 390 K, 00:00 UTC, left), which is mixed with air from the western Pacific (Western Pacific surface–origin tracer at 370 K and 390 K, 00:00 UTC, right). The calculated synoptic HALO flight track position at 27 August 2023 is shown at 00:00 UTC (black line). The ASMA boundaries (indigo line) are given by MSF = 357.0 $\times 10^3$ m^{2}s^{-2} at 370 K and MSF = 367.6 $\times 10^3$ m^{2}s^{-2} at 390 K for 27 August 2023 at 00:00. Climatological isentropic transport barriers (olive line) at 370 K (PV = 6.4 PVU) and at 390 K (8.6 PVU) are given. Time intervals 1–3 shown in Fig. 15 are marked in magenta.

14. *Fig. 10: Consider to refer to fig. 9 for recurring descriptions of the annotation etc.*

    Many thanks for this comment. We refer in caption of Figs. 10 and 13 to Fig. 6 to shorten the text in the figure captions and to avoid duplication.

15. *L409: Why outflow? South Asian air in F02 seems to be mainly within the ASMA (in interval 2).*

    Yes, we agree and revised the text as follows.

    Air masses measured in this monsoon-influenced filament 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 measured during research flight F02, where air originates mainly from the Indian subcontinent (IND, NIN, BoB; Figs. 7 and 8).

16. *L486: Case 1 also indicates that Pacific air might be transported around the outer edge of the ASMA. Then it is just a question of how this Pacific air is mixed with South Asian air during eddy shedding to the west. An outflow event at the western edge has not been analysed here?*

    We revised the text as follows to make the point clearer.

    Therefore, the chemical composition of air in the eastward outflow of the anticyclone differs from the western part of the ASMA.

References

Adcock, K. E., Fraser, P. J., Hall, B. D., Langenfelds, R. L., Lee, G., Montzka, S. A., Oram, D. E., Röckmann, T., Stroh, F., Sturges, W. T., Vogel, B., and Laube, J. C.: Aircraft-Based Observations of Ozone-Depleting Substances in the Upper Troposphere and Lower Stratosphere in and Above the Asian Summer Monsoon, J. Geophys. Res., 126, e2020JD033 137, https://doi.org/https://doi.org/10.1029/2020JD033137, 2021.

An, M., Western, L. M., Say, D., Chen, L., Claxton, T., Ganesan, A. L., Hossaini, R., Krummel, P. B., Manning, A. J., Mühle, J., O'Doherty, S., Prinn, R. G., Weiss, R. F., Young, D., Hu, J., Yao, B., and Rigby, M.: Rapid increase in dichloromethane emissions from China inferred through atmospheric observations, Nat Commun, 12, https://doi.org/10.1038/s41467-021-27592-y, 2021.

Claxton, T., Hossaini, R., Wild, O., Chipperfield, M. P., and Wilson, C.: On the Regional and Seasonal Ozone Depletion Potential of Chlorinated Very Short-Lived Substances, Geophys. Res. Lett., 46, 5489–5498, https://doi.org/https://doi.org/10.1029/2018GL081455, 2019.

Clemens, J., Vogel, B., Hoffmann, L., Griessbach, S., Thomas, N., Fadnavis, S., Müller, R., Peter, T., and Ploeger, F.: A multi-scenario Lagrangian trajectory analysis to identify source regions of the Asian tropopause aerosol layer on the Indian subcontinent in August 2016, Atmos. Chem. Phys., 24, 763–787, https://doi.org/10.5194/acp-24-763-2024, 2024.

Dubé, K., Tegtmeier, S., Bourassa, A., Laube, J. C., Engel, A., Saunders, L. N., Walker, K. A., Hossaini, R., and Bednarz, E. M.: Chlorinated very short-lived substances offset the long-term reduction of inorganic stratospheric chlorine, Commun Earth Environ, 6, 487, https://doi.org/10.1038/s43247-025-02478-9, 2025.

Feng, Y., Bie, P., Wang, Z., Wang, L., and Zhang, J.: Bottom-up anthropogenic dichloromethane emission estimates from China for the period 2005–2016 and predictions of future emissions, Atmospheric Environment, 186, 241–247, https://doi.org/https://doi.org/10.1016/j.atmosenv.2018.05.039, 2018.

Hoffmann, L., Günther, G., Li, D., Stein, O., Wu, X., Griessbach, S., Heng, Y., Konopka, P., Müller, R., Vogel, B., and Wright, J. S.: From ERA-Interim to ERA5: the considerable impact of ECMWF's next-generation reanalysis on Lagrangian transport simulations, Atmos. Chem. Phys., 19, 3097–3124, https://doi.org/10.5194/acp-19-3097-2019, 2019.

Hossaini, R., Chipperfield, M. P., Montzka, S. A., Leeson, A. A., Dhomse, S. S., and Pyle, J. A.: The increasing threat to stratospheric ozone from dichloromethane, Nat. Commun., 8, 15962, https://doi.org/10.1038/ncomms15962, 2017.

Kachula, O., Vogel, B., Günther, G., and Müller, R.: An optimization-based approach to track the Asian summer monsoon anticyclone across daily and interannual variability, Atmos. Chem. Phys., 25, 15 171–15 195, https://doi.org/10.5194/acp-25-15171-2025, 2025.

Konopka, P., Tao, M., Ploeger, F., Diallo, M., and Riese, M.: Tropospheric mixing and parametrization of unresolved convective updrafts as implemented in the Chemical Lagrangian Model of the Stratosphere (CLaMS v2.0), Geosci. Model Dev., 12, 2441–2462, https://doi.org/10.5194/gmd-12-2441-2019, 2019.

Konopka, P., Tao, M., von Hobe, M., Hoffmann, L., Kloss, C., Ravegnani, F., Volk, C. M., Lauther, V., Zahn, A., Hoor, P., and Ploeger, F.: Tropospheric transport and unresolved convection: numerical experiments with CLaMS-2.0/MESSy, Geosci. Model Dev., 15, 7471–7487, https://doi.org/10.5194/gmd-15-7471-2022, 2022.

Kunz, A., Sprenger, M., and Wernli, H.: Climatology of potential vorticity streamers and associated isentropic transport pathways across PV gradient barriers, J. Geophys. Res., 120, 3802–3821, https://doi.org/10.1002/2014JD022615, 2014JD022615, 2015.

Laube, J. C., Schuck, T. J., Baartman, S., Chen, H., Geldenhuys, M., van Heuven, S., Keber, T., Popa, M. E., Tuffnell, E., Voet, F., Vogel, B., Wagenhäuser, T., Zanchetta, A., and Engel, A.: Vertical distribution of halogenated trace gases in the summer Arctic stratosphere based on two independent air sampling methods, Atmos. Meas. Tech., 18, 4087–4102, https://doi.org/10.5194/amt-18-4087-2025, 2025.

Lauther, V., Vogel, B., Wintel, J., Rau, A., Hoor, P., Bense, V., Müller, R., and Volk, C. M.: In situ observations of CH_2Cl_2 and $CHCl_3$ show efficient transport pathways for very short-lived species into the lower stratosphere via the Asian and the North American summer monsoon, Atmos. Chem. Phys., 22, 2049–2077, https://doi.org/10.5194/acp-22-2049-2022, 2022.

Li, D., Vogel, B., Bian, J., Müller, R., Pan, L. L., Günther, G., Bai, Z., Li, Q., Zhang, J., Fan, Q., and Vömel, H.: Impact of typhoons on the composition of the upper troposphere within the Asian summer monsoon anticyclone: the SWOP campaign in Lhasa 2013, Atmos. Chem. Phys., 17, 4657–4672, 2017.

Li, D., Vogel, B., Müller, R., Bian, J., Günther, G., Ploeger, F., Li, Q., Zhang, J., Bai, Z., Vömel, H., and Riese, M.: Dehydration and low ozone in the tropopause layer over the Asian monsoon caused by tropical cyclones: Lagrangian transport calculations using ERA-Interim and ERA5 reanalysis data, Atmos. Chem. Phys., 20, 4133–4152, https://doi.org/10.5194/acp-20-4133-2020, 2020.

Li, D., Bian, J., Zhang, X., Vogel, B., Müller, R., and Güther, G.: Impact of typhoon Soudelor on ozone and water vapor in the Asian monsoon anticyclone western Pacific mode, Atmospheric Science Letters, 24, e1147, https://doi.org/https://doi.org/10.1002/asl.1147, 2023.

Malakar, P., Kesarkar, A., Bhate, J., Singh, V., and Deshamukhya, A.: Comparison of Reanalysis Data Sets to Comprehend the Evolution of Tropical Cyclones Over North Indian Ocean, Earth and Space Science, 7, e2019EA000 978, https://doi.org/https://doi.org/10.1029/2019EA000978, 2020.

Pan, L. L., Atlas, E. L., Honomichl, S. B., Smith, W. P., Kinnison, D. E., Solomon, S., Santee, M. L., Saiz-Lopez, A., Laube, J. C., Wang, B., Ueyama, R., Bresch, J. F., Hornbrook, R. S., Apel, E. C., Hills, A. J., Treadaway, V., Smith, K., Schauffler, S., Donnelly, S., Hendershot, R., Lueb, R., Campos, T., Viciani, S., D'Amato, F., Bianchini, G., Barucci, M., Podolske, J. R., Iraci, L. T., Gurganus, C., Bui, P., Dean-Day, J. M., Millán, L., Ryoo, J.-M., Barletta, B., Koo, J.-H., Kim, J., Liang, Q., Randel, W. J., Thornberry, T., and Newman, P. A.: East Asian summer monsoon delivers large abundances of very short-lived organic chlorine substances to the lower stratosphere, Proc. Natl. Acad. Sci., 121, e2318716 121, https://doi.org/10.1073/pnas.2318716121, 2024.

Pan, L. L., Atlas, E. L., Newman, P. A., Thornberry, T., Jucks, K. W., Toon, O. B., Randel, W. J., Liang, Q., Kinnison, D. E., Ueyama, R., Bresch, J. F., Honomichl, S. B., Smith, W. P., Hornbrook, R. S., Ziemba, L., Fujiwara, M., Apel, E. C., Barucci, M., Bianchini, G., Brown, M., Bui, T. P., Campos, T., Chin, M., D'Amato, F., Dean-Day, J., Diskin, G., Franchin, A., Gurganus, C., Iraci, L. T., Kim, J., Koo, J.-H., Lait, L. R., Lesko, K., Podolske, J. R., Rollins, A., Sakai, T., Shiraishi, K., Treadaway, V., Viciani, S., and Waxman, E.: The Asian Summer Monsoon Chemical and Climate Impact Project (ACCLIP): An Overview, Journal of Geophysical Research: Atmospheres, 130, e2025JD044 417, https://doi.org/https://doi.org/10.1029/2025JD044417, e2025JD044417 2025JD044417, 2025.

Ploeger, F., Diallo, M., Charlesworth, E., Konopka, P., Legras, B., Laube, J. C., Grooß, J.-U., Günther, G., Engel, A., and Riese, M.: The stratospheric Brewer–Dobson circulation inferred from age of air in the ERA5 reanalysis, Atmos. Chem. Phys., 21, 8393–8412, https://doi.org/10.5194/acp-21-8393-2021, 2021.

Riese, M., Hoor, P., Rolf, C., Kunkel, D., Vogel, B., Köllner, F., Pöhlker, M., Ploeger, F., Ungermann, J., Woiwode, W., Johansson, S., Bauer, R., Barmpounis, K., Borrmann, S., Brauner, P., Clemens, J., Dragoneas, A., Ekinci, F., Emig, N., Engel, A., Eppers, O., Fadnavis, S., Friedl-Vallon, F., Geldenhuys, M., Günther, G., Grooß, J.-U., Hegglin, M. I., Hoepfner, M., Jesswein, M., Joppe, P., Kaumanns, J., Kachula, O., Keber, T., Kretschmer, E., Lachnitt, H.-C., Lauther, V., Lloyd, P. E., Molleker, S., Müller, R., Neubert, T., Ort, L., Pöschl, U., Pöhlker, C., Rapp, M., Retzlaff, M., Rhode, S., Schneider, J., Schuck, T., Sinnhuber, B.-M., Spelten, N., Strobel, J., Tomsche, L., Turhal, K., van Luijt, R., Versick, S., Voigt, C., Volk, M., von Hobe, M., Weyland, F., Zahn, A., Ziereis, H., and Zlotos, L.: Long-range transport of polluted Asian summer monsoon air to high latitudes during the PHILEAS campaign in the boreal summer 2023, Bull. Am. Meteorol. Soc., https://doi.org/https://doi.org/10.1175/BAMS-D-24-0232.1, preprint, Online Publication: July 8, 2025, 2025.

Rolf, C., Vogel, B., Hoor, P., Afchine, A., Günther, G., Krämer, M., Müller, R., Müller, S., Spelten, N., and Riese, M.: Water vapor increase in the lower stratosphere of the Northern Hemisphere due to the Asian monsoon anticyclone observed during the TACTS/ESMVal campaigns, Atmospheric Chemistry and Physics, 18, 2973–2983, https://doi.org/10.5194/acp-18-2973-2018, 2018.

Say, D., Ganesan, A. L., Lunt, M. F., Rigby, M., O'Doherty, S., Harth, C., Manning, A. J., Krummel, P. B., and Bauguitte, S.: Emissions of halocarbons from India inferred through atmospheric measurements, Atmos. Chem. Phys., 19, 9865–9885, https://doi.org/10.5194/acp-19-9865-2019, 2019.

Smith, W. P., Pan, L. L., Ueyama, R., Honomichl, S., Campos, T., Viciani, S., D'Amato, F., Bianchini, G., Barruci, M., Hornbrook, R. S., Apel, E. C., Hills, A. J., Barletta, B., Atlas, E., Schauffler, S., Treadaway, V., Smith, K., Lueb, R., Hendershot, R., Donnelly, S., Rollins, A., Waxman, E., Novak, G., Huey, L. G., Tanner, D., Lee, Y. R., Bekemeier, C., and Bowman, K. P.: Transport by Asian Summer Monsoon Convection to the Upper Troposphere and Lower

Stratosphere During ACCLIP (2022), J. Geophys. Res., 130, e2024JD042 732, https://doi.org/https://doi.org/10.1029/2024JD042732, 2025.

Vogel, B., Müller, R., Günther, G., Spang, R., Hanumanthu, S., Li, D., Riese, M., and Stiller, G. P.: Lagrangian simulations of the transport of young air masses to the top of the Asian monsoon anticyclone and into the tropical pipe, Atmos. Chem. Phys., 19, 6007–6034, https://doi.org/10.5194/acp-19-6007-2019, 2019.

Vogel, B., Volk, C. M., Wintel, J., Lauther, V., Müller, R., Patra, P. K., Riese, M., Terao, Y., and Stroh, F.: Reconstructing high-resolution in-situ vertical carbon dioxide profiles in the sparsely monitored Asian monsoon region, Commun Earth Environ, 4, https://doi.org/10.1038/s43247-023-00725-5, 2023.

Vogel, B., Volk, C. M., Wintel, J., Lauther, V., Clemens, J., Grooß, J.-U., Günther, G., Hoffmann, L., Laube, J. C., Müller, R., Ploeger, F., and Stroh, F.: Evaluation of vertical transport in ERA5 and ERA-Interim reanalysis using high-altitude aircraft measurements in the Asian summer monsoon 2017, Atmos. Chem. Phys., 24, 317–343, https://doi.org/10.5194/acp-24-317-2024, 2024.