Response to Referee's (Referee #3) Comments

Review of "Investigating the role of typhoon-induced gravity waves and stratospheric hydration in the formation of tropopause cirrus clouds observed during the 2017 Asian monsoon" by Pandit et al.

This study analyzes backscatter sonde and optical particle counter measurements from balloons over Hyderabad, India to characterize properties of subvisible cirrus layer observed near the tropopause. They then investigate the formation mechanism of these cirrus cloud layers near the tropopause using a combination of back trajectories, satellite observations, and ERA5 reanalysis data. They conclude that overshooting convection from a typhoon created a hydration patch which was transported towards Hyderabad and ascended (via gravity waves) to form the cirrus layer. While the analyses of balloon data to characterize the cirrus cloud properties were interesting, the discussion on the formation mechanism of those clouds, particularly its ties to gravity waves, needs further development and clarification. Detailed comments are provided below.

Reply: First of all, we would like to thank the referee for carefully going through the manuscript and providing his/her constructive comments. In the following, our point-by-point response to the referee's comments (in black text) are presented in blue text.

Main Comments:

Although the combined use of various observations is generally a good idea, the frequent comparisons between measurements from different data sources at different locations and times (e.g., Table 2, Fig. 7, 10, 13) were difficult to interpret. This is especially problematic for this study since the phenomena of interest (i.e., overshooting convection, gravity waves) are small scale features that require coincident measurements. I suggest refining and limiting the selection of observations to only those that meet rigorous time and space matching criteria. I would also present the comparisons in a manner that is easily interpretable by the reader.

Reply: We thank the referee for bringing up this aspect. Tropopause cirrus clouds can be best studied with in-situ data (using balloons and aircraft) and ground-based and space-borne lidars owing to their high-sensitivity and high-vertical resolution. However, these observations are not available all the time and are limited to small spatial scales. With these limitations, we have tried our best to connect these small-scale observations with satellite and reanalysis data with the best possible coincidence available to us. It's challenging to get coincident measurements all the time at the desired location. This study investigates the role of a synoptic scale phenomenon (a typhoon) on the formation of tropopause cirrus clouds via typhoon-induced stratospheric hydration and gravity waves. It is to note that the impacts of overshooting convection and gravity waves associated with a typhoon are more intense, longer and have larger spatial extent in contrast to those of a mesoscale convective system. Several studies (as mentioned in the text: p30, lines 16-20) have suggested that semi-circular gravity waves generated from typhoon centre propagate horizontally through the troposphere, stratosphere, and the mesosphere in expanding spirals with horizontal wavelengths typically in the range of 50-500 km and periods from 1 hour to 1.6 days.

Our measurement coincidence criterion falls within this range. We further provide more details to address this aspect while responding to the referee's detailed comments.

I also found the discussion of the trajectory results to be somewhat incoherent. If the main purpose of using the backward trajectories is to show the influence from deep convection on cirrus clouds measured by the balloon, the most important quantity to show is the temperature and relative humidity evolution from the convection encounter to the measurement location. Trajectory results should be more concisely presented instead of across multiple figures. I would similarly reorganize other parts of the paper and make the paper more concise overall.

Reply: We thank the referee for raising this concern. We completely agree with the referee that the main purpose of using the back trajectories is to show the influence from deep convection on cirrus clouds measured by the balloon. In Fig. 5 and Fig. 6, we have shown this aspect. We also understand that the most important quantity to show is the temperature and relative humidity evolution from the convection encounter to the measurement site. We did show temperature along the trajectories in Figs. 11 and 12. Unfortunately, the relative humidity (RH) derived along the back-trajectories from the GEOS-FP data were not reliable in the UTLS region and therefore, we have not shown that in the manuscript. However, we have presented RH from Aura-MLS observations co-located with cirrus clouds observations from CALIOP at two locations intersecting the back-trajectories (see Fig. S10). In order to show the transport of water vapor from the typhoon towards Hyderabad, we have presented a Hovmöller diagram for water vapor mixing ratio from ERA5 reanalysis data (Fig. 10a).

Since we use 3D back-trajectories, we have shown the movement of air-parcels both horizontally (Fig. 5a and 11) and vertically (Figs. 5b, 12a and 12b) as a function of time and space. In addition to this, meteorological parameters such as temperature, vertical wind, and anvil clouds are also derived along the back-trajectories and shown in both horizontal and vertical directions. It is challenging to show these many parameters in just one or two figures. In each section, different aspects of the trajectories have been presented in different figures to support the findings of the investigation. We further provide more details about this aspect while responding to the referee's detailed comments.

Detailed Comments:

- P4: The temperature impact by tropical storms in Biondi et al. studies is fairly localized, and as such, I would not describe it as "a change in large-scale temperature fields in the TTL"

  Reply: We have removed that sentence in the revised manuscript.

- P11: Have the authors looked in the effects of trajectory uncertainties on the results? I'm assuming these are kinematic trajectories, whose dispersive nature may be concerning especially when calculating forward trajectories from UTLS levels.

  Reply: The dispersive nature of the trajectories is taken care of by initializing clusters of air-parcels which allow dispersion due to horizontal and vertical wind shears, representing the synoptic-scale dynamics (Fairlie et al., 2014; Pierce and Fairlie, 1993). The back-trajectories from the Langley trajectory model (LaTM) have been extensively used to study the dispersion of volcanic plume (Fairlie et al., 2014) in the UTLS region and also to map UTLS aerosols to deep convective clouds observed from geostationary satellites (Fairlie et al., 2014; Vernier et al., 2015, 2018, 2021).

This study neither uses any LaTM forward trajectories nor represents any sub-grid scale convective or turbulent dispersion. Moreover, the back-trajectories used in this study to investigate the convective influence do not go back in time for more than 3 days. Thus, the uncertainties due to the dispersion would be reduced.

- P12: Is the use of ERA5 cloud cover fraction necessary? Cloud fields in reanalyses are model products (Wright et al., 2020) and vary depending on prescribed boundary conditions, physical parameterizations (e.g., convection), data assimilation approach, and assimilated data. It is likely unsuited as "cloud observations". Rather, plotting the 100 hPa temperature (or cold point temperature) field may be more reliable.

  Reply: We thank the referee for this suggestion. In the revised manuscript, we have removed cloud fraction from Section 2.4.3 and used 100 hPa temperature instead of cloud fraction in Figure 3 (a) as suggested.

- P15: What do you mean by running HYSPLIT trajectories from different altitudes of the CL5? Are the trajectories run at multiple altitudes within the ~2 km thick cloud layer estimated from the balloon measurements? And these trajectories intersect the CATS orbit several hours later at the same altitude as the cirrus detected from CATS? Can you be more specific?

  Reply: We calculated HYSPLIT forward trajectories at three different altitudes (16.8 km, 17.8 km, and 18.3 km) within the vertical extent of CL5. These altitudes correspond to the locations of CL5 near its base altitude (16.8 km), the cold-point tropopause (17.8 km) and near the top altitude (18.3 km) of CL5, respectively. These trajectories are intersected by the CATS orbit after ~2.5 hours of the passage of the air-parcels coming from the CL5. This means that the tropopause cirrus clouds were detected by the CATS after the passage of air-parcels coming from the CL5, indicating their possible influence. We have added this information in the main text.

- Fig. 5a: Can you explain what is meant by "day fraction (UTC)"? This is confusing to me since the dots are supposedly showing backward trajectories from 23 Aug 2017 at 20 UTC. Time since balloon measurement may be easier to interpret.

  Reply: We thank the referee for pointing this out. Each dot represents the location of an air-parcel in longitude-latitude space with colour showing its time in days. We have changed the colourbar title to "Days in Aug 2017."

- Fig. 5: What is the temperature history of these trajectories? Are the parcels cooling as they reach the balloon measurement point when cirrus clouds were formed? Figs. 11 and

12 are discussed much later, but this is a key parameter to look at as is RH with respect to ice.

Reply: The temperature history of these trajectories is discussed in detail in Section 3.4.3 after investigating the possible role of deep convective clouds and stratospheric hydration in influencing the air-parcels. As we can see in Figs. 11 and 12 that the air-parcels have experienced several cooling and warming phases near the tropopause before reaching the balloon site, the air-parcels have undergone cooling as they reach the balloon measurement point where tropopause cirrus clouds were detected.

We thank the referee for bringing up the discussion of relative humidity with respect to ice (RHi) here. The water vapour information along the back-trajectories from GEOS-FP data was not reliable near the tropopause which led to poor estimates of RHi along the back-trajectories and hence not shown here. However, the profiles of RHi observed from the Aura-MLS on 22 and 23 August 2017 co-located with CALIOP which intersected the trajectories show RHi values greater than 100 % at 100 hPa (~16.8 km) level, indicating supersaturation (see Fig. S10).

Fig. 5: How are the parcels that descend backward in time between 115-125 degE in panel (a) represented in panel (b)? In the plan view, it looks like they are wrapped in the typhoon at 125-130 degE, which does not seem to be consistent with panel (b)?

Reply: The trajectories originating between 16 and19 km as shown in Fig. 5(b) do appear to be wrapped in the typhoon at 125-130° E when we change the scale of y-axis, thus, it is consistent with Fig. 5a (see the figure below). Since TTL region is the focus of this manuscript, we have only shown altitude region between 15 km and 20 km in Fig. 5b.

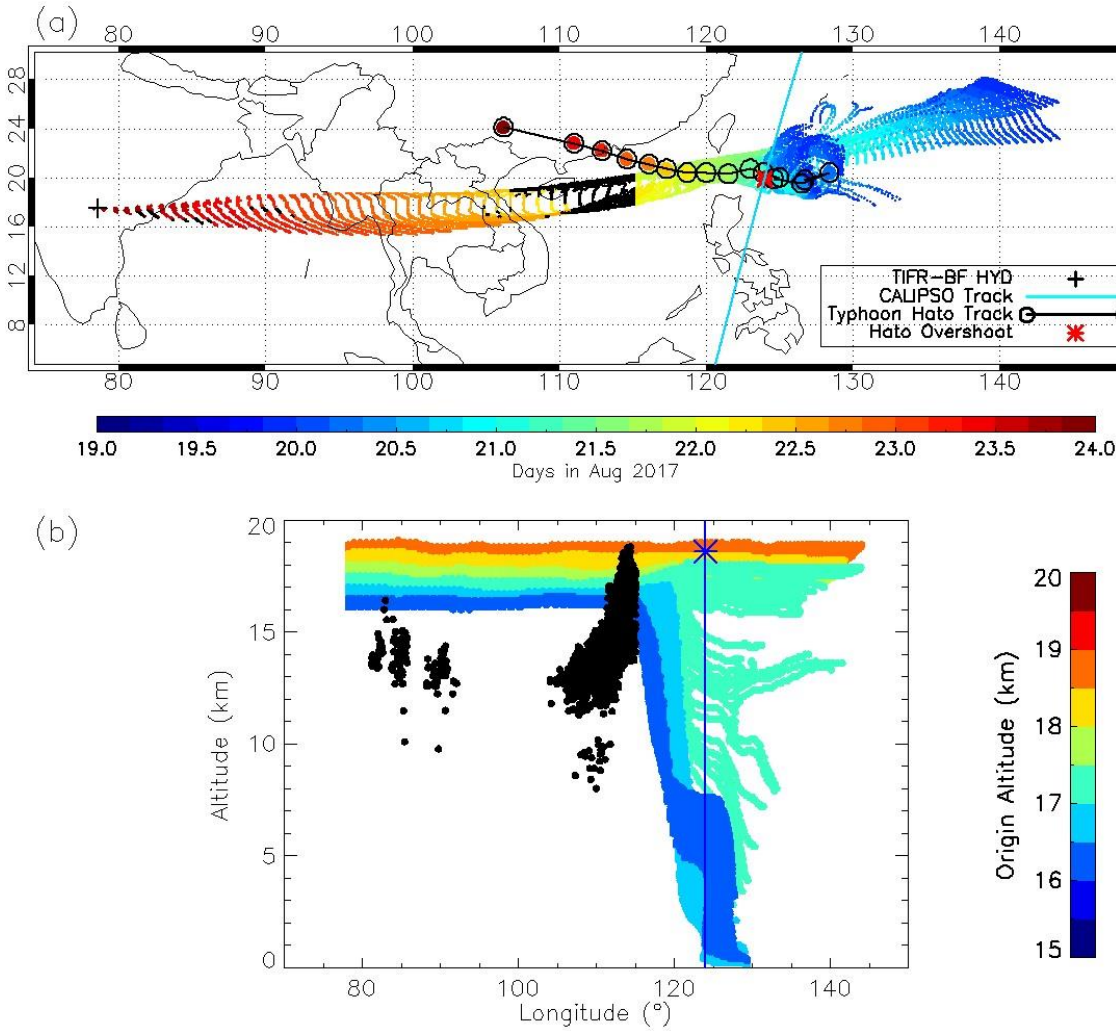

Figure 1) Five-day back-trajectories initialized on 23 August 2017 at 20:00 UTC from the balloon measurement locations at different altitudes between 16 and 19 km represented by colored dots as a function of latitude and longitude with colour showing the days in August 2017. The locations of deep convective anvil tops observed after 21 August 2017 from the Himawari-8 brightness temperature images at 10.4 µm wavelength channel that intersected the back-trajectories are shown by black dots. Typhoon Hato track is shown by black outlined coloured circles connected by black line with colour showing the day fraction. The night-time CALIPSO orbit track on 20 August 2017 between 17:27 and 17:40 UTC is shown by cyan line with the location of the overshooting cloud top shown by red asterisk. (b) Five day back-trajectories represented as a function of longitude and altitude with colour showing their origin altitude. The locations of the anvil top altitude that intersected with the back-trajectories are represented by black dots. The locations of CALIPSO overpass and the overshooting cloud top altitude are shown by blue vertical line and blue asterisk, respectively.

- P21: How exactly is the convective anvil top altitude determined from the brightness temperatures to quantify the convective influence? The text mentions that this is discussed in Section 2.4.1, but I don't see any description of this methodology.

Reply: The uncertainty in the estimation of anvil cloud top altitude is about 0.75 km relative to CALIOP. Griffin et al. (2016) found that ~75% (65%) of MODIS (geostationary) overshooting top heights were within ±500 m of the coincident Cloud Profiling Radar (CPR/CloudSat)-estimated heights. Nearly all were within 1 km of CloudSat.

We thank the referee for pointing out this mistake. We have discussed the convective anvil top altitude estimation from the brightness temperature in Sect. 2.3.3. We have made this correction in the revised manuscript.

- P21: Pixel resolution certainly impacts temperatures within a convective cloud, but that fact alone is insufficient to claim that "the highest overshooting tops likely exceeded 18 km height". More concrete evidence of this is needed to make such a claim.

  Reply: We understand the referee's concern here and this is why we used the word "likely" in the text. We tried to bring more confidence to Himawari-8 observations of cloud-tops by looking at nearest ground-based Doppler Weather Radar (DWR) observations available from IMD Machilipatnam station which also indicated towards the presence of such deep convective clouds. In lines 11-13 of Page 21, we have mentioned this. However, the radar images prior to 1200 UTC, when those convective clouds were at their peak altitude (as observed in Himawari-8 images), were unavailable to confirm the presence of overshooting tops exceeding 18 km. Moreover, the spatial scale and lifetime of those convective clouds were also small. In line 14-15, we also mention that we cannot fully rule out the probable influence of local convection.

- Table 2: While I understand the attempt to describe the temperature evolution of the parcel sampled, the disparate data sources (radiosonde, GNSS-RO), locations and times of these measurements make it difficult to say anything about the actual temperature evolution/effect, especially since we expect temperature perturbations on small spatial and temporal scales that greatly affect the cirrus cloud formation. It would make more sense to look at the temperatures along the backward trajectories to describe the evolution (like Fig. 11) and see if those agree with temperature observations at matching times and locations.

  Reply: The main purpose of including radiosonde and GNSS-RO temperature profiles in Table 2 is to show the variation of cold-point tropopause altitude and temperature over Hyderabad region during the 24-hour period (23-24 August 2017) before, during, and after the balloon measurements. We do not have observations near the tropopause over Hyderabad all the time and this made us use the nearest possible (within 332 km) temperature profiles available from radiosonde and GNSS-RO. Except GNSS-RO observation, all radiosonde observations are within 136 km. Given the large horizontal extent (> 500 km) of the tropopause cirrus clouds as seen from CATS observations on 24 August 2017 at around 0136 UTC, we can say that the fluctuations in temperature may not be just limited to small spatial scales (see Fig. 1b for reference).

  Regarding the referee's suggestion, the temperature used along the back-trajectories is extracted from GEOS-FP data which has limited vertical resolution to accurately infer the cold-point tropopause altitude. This is evident from Figure 13 (b) to (d) where we discussed the presence of tropopause cirrus clouds observed from COBALD, CALIOP, and CATS along the back-trajectories while identifying the CPT altitude using nearest possible radiosonde and GNSS-RO observations.

- Fig. S3: (a) It would be good to include latitude and longitudes. (b) How realistic is the ERA5 water vapor (compared to observations like MLS)? Are you claiming that the wet anomalies are from the typhoon injected water and ice? (c) is x-axis the latitude?

  Reply: We have added latitude and longitudes in Fig. S3(a).

  The comparison of ERA5 water vapor with balloon-borne cryogenic frost-point hygrometer (CFH) during the Asian Summer Monsoon (ASM) has been discussed in Section 2.4.3. On an average, ERA5 water vapor overestimates by 0.7-0.9 ppmv compared to CFH (Brunamonti et al., 2019) and by ~ 2 ppmv compared to MLS observations (Khordakova et al., 2021; Sivan et al., 2022).

  The encircled wet anomalies from ERA5 at 1200 UTC shown in Fig. S3(b) are likely from the encircled deep convective clouds shown in Fig. S3(a).

  No, x-axis in Fig. S3(c) is longitude. We have labelled x-axis and y-axis in the revised figure.

- Fig. S4: Two temperature profiles are compared, but they are again from two different sources at two different locations at two different times. It is overreaching to claim from this figure alone that "tropopause temperature and tropopause altitude might be substantially reduced by the overshooting convection". Or is this meant to approximate the cold-point tropopause altitude?

  Reply: Yes, the two temperature profiles are just meant to approximate the cold-point tropopause altitude near the typhoon overshoot.

- Fig. 6: Do the back trajectory segments shown here exactly match the trajectories in Fig. 5b? It would be better if you could somehow combine these plots into one since they are approximately showing the same information.

  Reply: The back trajectory segments shown in Fig. 6 are the snapshot of back-trajectories on 22 August 2017 at 1900 UTC when they intersected CALIPSO overpass which observed a tropopause cirrus cloud layer in the outflow of typhoon *Hato*. These trajectories are different from those shown in Fig. 5b which showed 5-day back-trajectories initialized from the balloon measurement location between 16 and 19 km altitude. Adding this figure to Fig. 5 would make it difficult for the reader as there will be too much information in the same figure; we therefore decided to keep it separate.

- Fig. 7: Where are the MLS observations (track) on the map? It would be helpful to show those to interpret panel (b). Due to the deep averaging kernel of MLS, it is not clear that the 6.5 ppmv water at 82.5 hPa actually represents enhanced water above the CPT as you suggest in p23. They could be contributed from enhanced moisture near the CPT.

Reply: We thank the referee for this suggestion. In the revised figure, we have added MLS track on the map.

We agree with the referee's concern on the deep averaging kernel of MLS and its impact on the magnitude of water vapor mixing ratio values near the CPT. We have rephrased this sentence in the revised manuscript.

- Fig. 9: Is (a) identical to Fig. S4? If so, this needs to be noted (and S4 could be removed). If not, please explain. How do the MLS values compare with the mean ERA5 water vapor shown in (b)? Rather than color coding the dots by the date, consider coloring the dots with the WV mixing ratios?

  Reply: Yes, Fig. 9(a) is identical to Fig. S4 except the location of nearest radiosonde sounding, GNSS-RO sounding and the maximum anvil top height of typhoon Hato overshoot estimated from Himawari-8 images on 22 August 2017 at 0900 UTC shown on the map. We have removed Fig. S4 (top panel) in the revised supplementary material and added the location of GNSS-RO sounding and maximum anvil top height in Fig. 9(a) in the revised manuscript.

  The ERA5 water vapor mixing ratio is overestimated by ~ 2 ppmv compared to MLS observation (Khordakova et al., 2021; Sivan et al., 2022).

  Please note that the MLS tracks shown in Fig.9b are for different days between 20 and 23 August 2017 while the map shows two-day (22 and 23 August 2017) mean water vapor mixing ratio at 70 hPa pressure level from ERA5 showing the transport of enhanced water vapor. Hence, they are not compared. The magnitude of MLS water vapor mixing ratio at different pressure levels on different dates can be seen in Fig. 10b.

- Fig. 10: It would better to plot panels (b) to (e) in chronological order to see the decreasing magnitude (or select one representative location and combine the four profiles in one plot).

  Reply: We thank the referee for this suggestion. We have modified the panels (b) to (e) in chronological order.

- P28: Have the authors checked to confirm that supersaturation (and how high of a supersaturation) is achieved along the trajectories to allow for ice nucleation?

  Reply: Unfortunately, the relative humidity derived along the back-trajectories from the GEOS-FP data are not reliable in the UTLS region and therefore, we have not shown them in the manuscript. However, we have presented relative humidity with respect to ice (RHi) from Aura-MLS observations co-located with cirrus cloud observations from CALIOP at two locations intersecting the back-trajectories (see Fig. S10). Profiles of RHi observed from the Aura-MLS on 22 and 23 August 2017 co-located with CALIOP show RHi values greater than 100 % at 100 hPa (~16.8 km) level, indicating supersaturation that resulted in ice formation. This is mentioned in the main text on p31, lines 25-27.

- Fig. 12: What resolution analyses are used for these trajectories? Is the resolution high enough to capture gravity waves? I see that the use of MERRA-2 reanalysis data is mentioned later on p31, but this should be discussed earlier along with Fig. 12. Also, how exactly are the vertical wind speeds derived along the trajectories in (b)? I presume the vertical winds are used to compute the kinematic trajectories.

  Reply: Three dimensional trajectories are computed using NASA Langley Trajectory Model (LaTM) which is driven by NASA Global Modeling and Assimilation Office (GMAO) Goddard Earth Observing System Version 5 (GEOS-FP) analyzed winds with a native horizontal resolution of 0.25° x 0.3125°. We use 6-hourly, time averaged wind fields resolved to horizontal resolution of 1.25° x 1° with 72 levels in the vertical having a resolution of ~1 km near the tropopause (Fairlie et al., 2014).

  MERRA-2 temperature data were not used in this study. We have corrected this error by changing "MERRA-2" to GEOS-FP in the revised manuscript. We thank the referee for pointing it out.

  The vertical wind speeds are derived from latitude, longitude, altitude, and time information of the air-parcels. The vertical wind speed is used here to infer the upward or downward motion of the air-parcels which could indicate, respectively, towards cooling or warming associated with the air-parcels. Though the magnitude of the vertical wind speed may not be accurate in comparison to the observations (which we do not have), they do give a qualitative idea about the cooling and warming experienced by the air-parcels along the back-trajectories. It is interesting to see that the cooling and warming are associated with upward and downward motion of the air-parcels, respectively. Yes, vertical winds from the GEOS-FP are used to compute kinematic trajectories.

- Fig. 13: The purpose of this figure is unclear. The text seems to suggest that the purpose is to show the cold anomalies using high resolution data (and their impact cirrus), but it is difficult to interpret where and when these measurements are taken in relationship to the balloon measurements and trajectories. The time and lat/lon are noted in the figure caption, that without a map or time series to place them in larger context, it is very difficult to interpret this figure. It is even unclear whether the measurements plotted in one panel are coincident in time and location (they don't appear to be).

  Reply: This figure is used to show the location of cold-point tropopause, unresolved by GEOS-FP temperature profiles, and the presence of tropopause cirrus clouds as observed by CATS, CALIOP, and COBALD shown in Figs. 11 and 12. The purpose of Fig. 13 is clearly mentioned on page 32, lines 12-25. It was difficult to locate the cold-point tropopause from Fig. 12, so we have used nearest possible temperature observations (within 400 km and 6 hours) with respect to CATS and CALIPSO profiles as shown in Figs. 11 and 12. This co-location criterion (within 400 km and 6 hours) is mentioned in the main text (p31, line 18). Each panel in Fig. 13 shows clearly the location of cold-point tropopause and presence of thin tropopause cirrus cloud layers.

The location and date/time information of these measurements are shown on a map in Fig. 11. We provide the date/time and location of these measurements on each panel in the revised manuscript for clarity.

- Fig. 14: Temperatures were anomalously cold at ~17.9 km near the CPT on 23 Aug, but the tropopause altitudes presumably vary across all the profiles used to calculate the mean. Therefore, panel (a) alone is not sufficient to claim that the CPT was unusually cold on that day. It might make more sense to calculate the anomalies in tropopause relative coordinates. I also do not follow the argument that the variations above 15 km are likely due to waves ("wave-like pattern"). Cooling is likely associated with cirrus formation, but the suggested role of waves from Fig. 14 vertical profiles seems circumstantial at best. The authors mention a "Hodograph analysis of radiosonde data" to show evidence of gravity waves and derive their characteristics, but no description of the analysis is provided.

  Reply: Thanks for raising this aspect. Please note that in Fig. 14, we are presenting perturbation profiles after removing the monthly mean profile, and there is a ~8°C cooling on August 23 (Fig. 14 a). While it is true that the CPT altitudes may not be the same on all the days which are used to estimate the mean profile, we only assert that there is significant cooling near the tropopause. This indicates that the background mean was much warmer on most days of that month. Since demonstrating that the CPT was the coldest is not the primary focus of this plot, we have not estimated the tropopause relative coordinates.

  Regarding the wave-like pattern, please note that in all the perturbation profiles, a systematic variation with positive and negative values is evident, generally attributed to waves. The difference between two positive peaks (or negative peaks) gives the vertical wavelength of the wave. As there can be a superimposition of many waves, we observe smaller perturbations superimposed on larger perturbations. For more details on the extraction of wave properties and hodograph, please refer to Ratnam et al. (2006), specifically their Fig. 9. Additionally, for perturbation profiles in all three components (T, U, and V), refer to their Fig. 5.

  The hodograph analysis is performed using a method described in Leena et al. (2012) which has already been mentioned in the text (page 35, lines 9-12). We have added the method description in sub-section 2.2.3 of the data and method section. We have also included a figure (Fig. S11) for the hodograph analysis in the revised supplementary information.

References:

Wright, J. S., Sun, X., Konopka, P., Krüger, K., Legras, B., Molod, A. M., Tegtmeier, S., Zhang, G. J., and Zhao, X.: Differences in tropical high clouds among reanalyses: origins and radiative impacts, Atmos. Chem. Phys., 20, 8989–9030, https://doi.org/10.5194/acp-20-8989-2020, 2020

Brunamonti, S., Füzér, L., Jorge, T., Poltera, Y., Oelsner, P., Meier, S., Dirksen, R., Naja, M., Fadnavis, S., Karmacharya, J., Wienhold, F. G., Luo, B. P., Wernli, H., and Peter, T.: Water Vapor in the Asian Summer Monsoon Anticyclone: Comparison of Balloon-Borne Measurements and ECMWF Data, Journal of Geophysical Research: Atmospheres, 124, 7053–7068, https://doi.org/10.1029/2018JD030000, 2019.

Fairlie, T. D., Vernier, J.-P., Natarajan, M., and Bedka, K. M.: Dispersion of the Nabro volcanic plume and its relation to the Asian summer monsoon, Atmospheric Chemistry and Physics, 14, 7045–7057, https://doi.org/10.5194/acp-14-7045-2014, 2014.

Griffin, S. M., Bedka, K. M., and Velden, C. S.: A Method for Calculating the Height of Overshooting Convective Cloud Tops Using Satellite-Based IR Imager and CloudSat Cloud Profiling Radar Observations, Journal of Applied Meteorology and Climatology, 55, 479–491, https://doi.org/10.1175/JAMC-D-15-0170.1, 2016.

Khordakova, D., Rolf, C., Grooß, J.-U., Müller, R., Konopka, P., Wieser, A., Krämer, M., and Riese, M.: A case study on the impact of severe convective storms on the water vapor mixing ratio in the lower mid-latitude stratosphere observed in 2019 over Europe, Dynamics/Field Measurements/Stratosphere/Physics (physical properties and processes), https://doi.org/10.5194/acp-2021-749, 2021.

Pierce, R. B. and Fairlie, T. D. A.: Chaotic advection in the stratosphere: Implications for the dispersal of chemically perturbed air from the polar vortex, Journal of Geophysical Research: Atmospheres, 98, 18589–18595, https://doi.org/10.1029/93JD01619, 1993.

Ratnam, M. V., Tsuda, T., Shibagaki, Y., Kozu, T., and Mori, S.: Gravity Wave Characteristics over the Equator Observed During the CPEA Campaign using Simultaneous Data from Multiple Stations, Journal of the Meteorological Society of Japan. Ser. II, 84A, 239–257, https://doi.org/10.2151/jmsj.84A.239, 2006.

Sivan, C., Kottayil, A., Legras, B., Bucci, S., Mohanakumar, K., and Satheesan, K.: Tracing the convective sources of air at tropical tropopause during the active and break phases of Indian summer monsoon, Clim Dyn, 59, 2717–2734, https://doi.org/10.1007/s00382-022-06238-9, 2022.

Vernier, H., Rastogi, N., Liu, H., Pandit, A. K., Bedka, K., Patel, A., Ratnam, M. V., Kumar, B. S., Zhang, B., Gadhavi, H., Wienhold, F. G., Berthet, G., and Vernier, J.-P.: Exploring the inorganic composition of the Asian Tropopause Aerosol Layer using medium-duration balloon flights, Atmospheric Chemistry and Physics Discussions, 1–30, https://doi.org/10.5194/acp-2021-910, 2021.

Vernier, J.-P., Fairlie, T. D., Natarajan, M., Wienhold, F. G., Bian, J., Martinsson, B. G., Crumeyrolle, S., Thomason, L. W., and Bedka, K. M.: Increase in upper tropospheric and lower stratospheric aerosol levels and its potential connection with Asian pollution, Journal of Geophysical Research: Atmospheres, 120, 1608–1619, https://doi.org/10.1002/2014JD022372, 2015.

Vernier, J.-P., Fairlie, T. D., Deshler, T., Ratnam, M. V., Gadhavi, H., Kumar, B. S., Natarajan, M., Pandit, A. K., Raj, S. T. A., Kumar, A. H., Jayaraman, A., Singh, A. K., Rastogi, N., Sinha, P. R., Kumar, S., Tiwari, S., Wegner, T., Baker, N., Vignelles, D., Stenchikov, G., Shevchenko, I., Smith, J., Bedka, K., Kesarkar, A., Singh, V., Bhate, J., Ravikiran, V., Rao, M. D., Ravindrababu, S., Patel, A., Vernier, H., Wienhold, F. G., Liu, H., Knepp, T. N., Thomason, L., Crawford, J., Ziemba, L., Moore, J., Crumeyrolle, S., Williamson, M., Berthet, G., Jégou, F., and Renard, J.-B.: BATAL: The Balloon Measurement Campaigns of the Asian Tropopause Aerosol Layer, Bulletin of the American Meteorological Society, 99, 955–973, https://doi.org/10.1175/BAMS-D-17-0014.1, 2018.