MS No.: egusphere-2023-2094 – Influence of radiosonde observations on the sharpness and altitude of the midlatitude tropopause in the ECMWF IFS

By Krüger et al. (2023)

Reply to review #2

Dear Reviewer, we are grateful for your positive review of our manuscript, the appreciation of our study and that you recommend it for publication in WCD. Your comments helped us to improve the manuscript. Below, we answer each particular comment using a blue font. We also added a revised version that includes all corrections using track changes.

General comments

The paper addresses the representation of tropopause sharpness in forecast data and studies the effect of radiosonde observations on the assimilated tropopause structure.

For this purpose, the authors use more than 9700 radiosonde profiles in autumn 2016. Out of these 500 sondes were released as additional soundings in the frame of the NAWDEX experiment. These are used for an IFS observing system experiment with and without these additional soundings. For the full data set the authors analyze the emerging increments, innovations and residuals of temperature, wind (as well as shear) and static stability. Importantly they do this in tropopause relative coordinates to extract the effect of the assimilation of additional soundings on the tropopause thermal structure and winds.

In general their analysis clearly shows that the sondes lead to a sharpening of the tropopause in the assimilation. They further split the data according to Brunt Väisälä frequency in sharp, smooth and medium gradient tropopause cases and show that the sharpest tropopauses require the strongest increments, similar for the winds.

Overall, they found a sharpening of the tropopause with increased N^2_{max} and increased shear values from positive at the wind maximum to negative above the tropopause. In particular they infer from a comparison with and without the additional sondes a substantial contribution of the additional sondes to the assimilation. They also show that the analysis tropopause altitude is shifted towards the sounding observations. The comparison of the OSE runs highlights that the main contribution to the tropopause sharpening can be attributed to the radiosondes.

The only point which could be discussed by the authors is the role of humidity as possible reason for the temperature deviations at the tropopause (see below), though the humidity is not assimilated, it might explain at least partly the discrepancies of tropopause sharpness compared to the observations.

Overall the paper is very clear, well-structured and each analysis step is clearly motivated. The methods are well documented and appropriate, the emerging conclusions are scientifically sound - it was a pleasure to read.

The paper clearly merits publication in WCD and I see only minor points.

---

l.100: Although moisture is not assimilated the incorrect representation in the IFS, it may lead to larger temperature differences above e.g. cirrus clouds compared to clear sky observations. Cirrus occurrence in observational data might be misrepresented or missing in the IFS data, particularly for the N^2_max cases (i.e. ridge regions). Humidity is not assimilated and therefore not analyzed by the authors. Nonetheless it could be discussed (maybe in the final discussion) as possible cause for the misrepresentation of temperature at the tropopause. Would it be possible to relate the temperature increment at the sounding location to the observed humidity compared to the background humidity? A larger increment for different saturation conditions for IFS versus sounding would provide a potential explanation of temperature increments at higher tropopauses.

We agree with the reviewer that it would be very interesting to further study the connection between temperature and humidity errors in the UTLS. In principle, the passive (= not assimilated, but contained in the files) humidity data is also monitored, which we did not consider in this study. Using such data would allow to correlate temperature bias and increments with the cloud and moisture at the tropopause. Such an investigation would be feasible; however, it is beyond the scope of this study (temperature and wind influence of data assimilation). In our manuscript we refer to the study by Bland et al. (2021) at several points which provides a detailed analysis about the relation of temperature and moisture errors at and above the tropopause. Please note that we revised the discussion following a comment by the other reviewer, which we hope also addresses your comment (p.21, ll.487-494):

"The remaining LS cold bias in the analysis (0.2 K) corresponds to previous assessments (Radnóti et al., 2010) and is driven by radiative cooling due to water vapor (Sheperd et al., 2018; Bland et al., 2021), which is systematically overestimated at those levels (Krüger et al., 2022). Recent changes at the ECMWF reduced but not fully removed the bias in the IFS (Polichtchouk et al., 2021). The warm bias (1 K) at the tropopause in the IFS was related to the finite vertical resolution of the IFS incapable of fully resolving the tropopause (Ingleby et al., 2016), the assimilation of warm-biased aircraft data at tropopause flight levels (Ingleby et al., 2017) and the moist bias in the LS of the IFS (Bland et al., 2021). The magnitude of the warm bias (about 1.2 K) at the tropopause is about 2-3 times stronger than the corresponding warm bias reported in Bland et al. (2021)."

Fig.2 and related discussion: How does the altitude distribution of the 500 additional sondes compare to the rest? Could you add the PDF for those additional 500 soundings as separate contour?

That's a valid point. In the revised version of the manuscript, we added the tropopause altitudes distribution of the additional NAWDEX sounding (see the following figure). It clearly shows that due to the lower number of profiles at latitudes < 40°N less high tropopause altitudes (14-15 km) was observed.

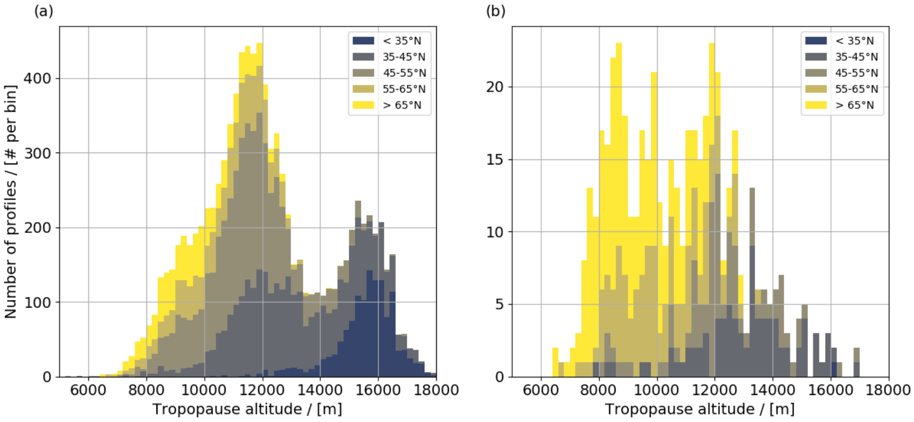

Figure 2: Stacked distribution of LRT_{YO} with 0.2 km bin size for (a) all 9729 radiosondes and (b) the additional 497 radiosondes observed during NAWDEX. The colouring shows the latitude of the radiosonde stations (10° bins).

In the revised manuscript we included the following paragraph to describe that (p.7, ll. 200-206):

“The left mode represents profiles with a high frequency (75 % of the profiles) of LRT altitudes at 10-14 km (see Fig. 2a) which is typical for the midlatitudes in autumn (e.g., Hoffmann and Spang, 2022; Krüger et al., 2022). Its broad spectrum is related to the variability of the midlatitude tropopause in different synoptic situations, e.g. in ridges and troughs (Hoerling et al., 1991). The right mode (LRT > 14 km; 25 % of the profiles) with its smaller maximum indicates profiles in the subtropics. The LRT distribution for the additional NAWDEX radiosondes (Fig. 2b) does not exhibit a corresponding second peak, due to the low number of soundings conducted at latitudes < 40 °N.”

Hoerling, M. P., Schaack, T. K., and Lenzen, A. J.: Global Objective Tropopause Analysis, Mon. Weather Rev., 119, 1816–1831, https://doi.org/10.1175/1520-0493(1991)119<1816:GOTA>2.0.CO;2, 1991.

Since the subtropical tropopause and the extratropical tropopause have partly different drivers, how do the results change when only considering extratropical tropopauses with altitudes less than 14000 m? Wouldn't one expect different effects of the assimilation of the mainly extratropical 500 soundings for the extratropical tropopause compared to the subtropical tropopause?

Thank you for this comment. A separate analysis for the sub-tropics and mid-latitude was also suggested by the other reviewer: Based on the observed tropopause altitudes in Fig. 2 we define profiles with an LRT >14 km as sub-tropical (25 % of the profiles) and LRT <14 km as mid-latitude profiles (75 %). The tropopause-relative profiles of observed temperature, N^2, wind and wind shear as well as the increments are shown for both classes in Figure S2. Compared to the mean midlatitude profiles which shows similar distributions as for the overall data set (compare Fig. 5). The sub-tropical profiles exhibit a considerably lower temperature in the entire UTLS, a weaker LS temperature inversion, a cooler tropopause and furthermore show continuously decreasing wind speed with altitude and no wind maximum being located near the tropopause. This represents a typical temperature and wind distributions one might expect poleward of the sub-tropical jet. We consider this an interesting finding relevant for the reader and decided to add Fig. S2 to the Supplement. In addition, we added the following description in Sect. 2.2 (p.9, ll.226-228 in the revised version):

“A separate analysis of extratropical (LRT < 14 km) and sub-tropical (LRT > 14 km) observations reveals similar shapes for the extratropical and the overall data (see Fig. S2a-d). The sub-tropical mean profiles

exhibit lower temperatures in the entire UTLS, a weaker temperature inversion in the LS and no wind maximum being located near the tropopause.”

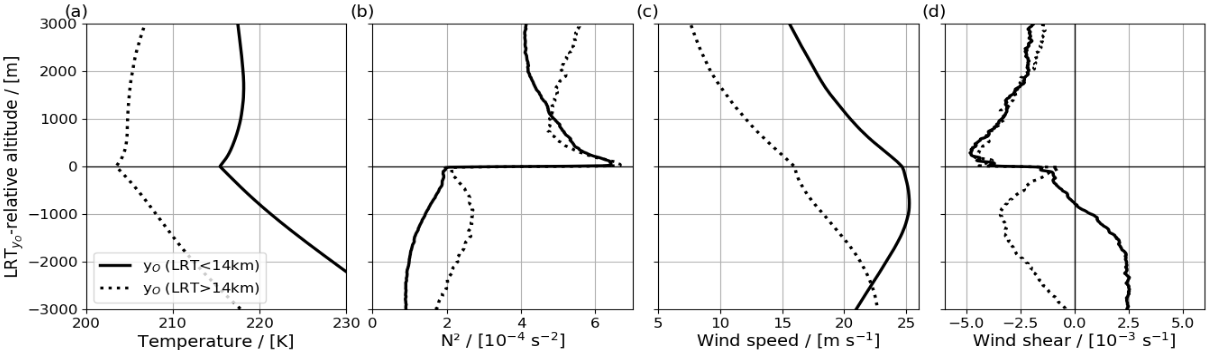

Figure S2: LRT$_{yO}$–relative mean profiles of (a) temperature, (b) N², (c) wind speed, (d) wind shear for profiles associated with the mid-latitudes (LRT$_{yO}$ < 14 km; solid) sub-tropics (LRT$_{yO}$ > 14 km; dashed).

In addition, we provide a plot for the average increments (Fig. S3). Increments of sub-tropical profiles are weaker, but still point in the same direction as in the midlatitudes. The wind speed increments are smaller in the upper troposphere at lower wind speeds. We added Fig. S3 to the Supplement and a description to Sect 3.2 (p.11, ll. 270-272 in the revised version).

“A separate analysis of mid-latitude and sub-tropical increments (Fig. S3) shows that the latter are weaker. However, as the increments in both regions point in the same direction, the complete data is considered for the statistical analysis in the remainder of this article.”

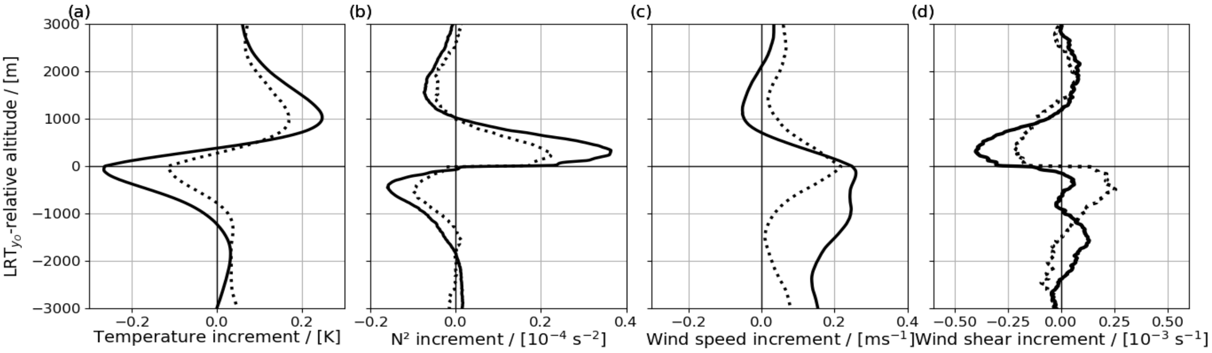

Figure S3: as in Fig. S2 but for increments.

l.43: Please also refer to the work of Kaluza et al. 2021 (WCD) who showed the existence of a shear layer in tropopause relative coordinates in ERA5.

References: Kaluza, T., Kunkel, D., and Hoor, P.: On the occurrence of strong vertical wind shear in the tropopause region: a 10-year ERA5 northern hemispheric study, Weather Clim. Dynam., 2, 631–651.

We are grateful for providing this reference. In l.43 (p1) we describe the tropopause structure as observed by a radiosonde climatology according to Birner et al. (2002). However, we included this reference in the Discussion (p.22, ll. 505-509):

“The observed vertical wind shear profile is characterized by positive values below and negative above the wind maximum as well as by a sharp increase of negative shear across the tropopause. The enhanced (negative) shear in the 1 km layer above the tropopause in the observations is also present

in the ECMWF, which is consistent with previous findings (Schäfler et al., 2020; Kaluza et al., 2021); its magnitude, however, is considerably weaker in the background and analysis as compared to the observations."

l.484/485: Sentence reads strange, please rephrase.

We revised the whole paragraph to better describe increments of wind speed and wind shear. As a result, this sentence was removed.