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A comparison between thermal tropopauses derived from mandatory and significant levels for the Indian subcontinent upper-air network

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Abstract

Differences between lapse rate tropopauses (LRTs) and LRT-like tropopauses retrieved from mandatory levels (LRTMs) were studied for height, pressure and temperature at 37 locations of the Indian subcontinent on a long-term annual, summer and winter basis covering the period 1973–2015. LRTM is usually found below LRT and statistical distinctions hinder the use of the former tropopause as a replacement for the latter one, yet significant positive Spearman's correlations show a relationship through a monotonic increasing function that enable the estimation of LRT variables from the corresponding LRTM ones. The slope and the intercept for a linear function relating corresponding variables were obtained at each location.

Keywords: **thermal tropopause; mandatory levels; Indian subcontinent**

1. Introduction

The tropopause is the layer that separates the troposphere from the stratosphere. Temperature in the former (latter) layer decreases (increases) with height. The lapse rate tropopause (LRT) determines the region at which the lapse rate changes its sign. The World Meteorological Organization (WMO) defines LRT as 'the lowest level at which the lapse rate decreases to 2 °C km^{-1} or less, provided that the average lapse rate between this level and all higher levels within 2 km does not exceed 2 °C km^{-1}' (WMO, 1992). The last condition avoids labeling low-level inversions as tropopauses. The definition permits the direct calculation of LRTs from radiosonde ascents, but they should be obtained from significant levels since it is at them where abrupt changes of thermodynamic variables occur.

Radiosondes at most upper-air stations show no recent issues with the report of significant levels (Simmons, 2011) but past records may lack them, hindering the operational retrieval of LRTs. One way to overcome this is to derive LRTs from mandatory levels, i.e. pressure levels at which temperature and wind data must be reported (WMO, 1992). Biases between LRTs and lapse rate tropopauses calculated from mandatory levels (LRTMs) are latitude-dependent (Zängl and Hoinka, 2001; Reichler *et al.*, 2003). Considering the advantages of the tropopause for assessing anthropogenic effects (Santer *et al.*, 2003), a direct application for LRTMs is their employment in tropopause trend studies, including the recovery and analysis of old radiosonde records registering only mandatory levels. Even at radiosonde void regions, long tropopause records can be operationally generated from historic reanalyses (e.g. The Twentieth Century Reanalysis, Compo *et al.*, 2011). It is therefore important for such purposes to know how LRTM relates to LRT.

Intra- and inter-seasonal variability in the Indian subcontinent, which ranks among the highest variabilities in the World, prompted the study of the region. The goal of the paper is to compare LRTM with LRT in the long-term annual and seasonal means for upper-air stations that span tropical and subtropical latitudes in the region in order to establish the differences and whether the LRTM is a suitable replacement for LRT. Given that LRTMs can be easily obtained from a variety of products with their output at fixed levels (e.g. reanalyses and circulation models), ways to estimate LRT from LRTM are also presented.

2. Data and methodology

The study was carried out using radiosonde ascents from the University of Wyoming's worldwide radiosonde database (http://weather.uwyo.edu/upperair/sounding.html). Radiosondes from 39 upper-air stations in India and one in Bangladesh were used. They are shown in Table S1, Supporting information along with the period spanned at each location: most of them extend from January 1973 to December 2015. Average radiosonde availability is above two thirds of the total at half of the stations. Owing to relocations, the time series at three stations were amalgamated to form a single record (see Table S1). Hence, the net number of locations in this study is 37. The location of these stations appear in Figure S1.

Individual radiosondes include both mandatory and significant levels. The number of either level varies spatially and temporally. Figure S2 shows the average annual percentages of significant levels for the study region, evidencing a net increase in the recent years. Figure S2 also shows the average annual number of significant levels between 250 hPa and 50 hPa. Mandatory and significant levels were separated in order to calculate LRTMs and LRTs. Following the WMO definition, LRTs were obtained from significant levels with an algorithm that had the ability to calculate up to five different tropopauses from each ascent. Table S2 shows the percentages of detected LRTs and the breakdown into single and double events. Single tropopauses represent most of the cases at all sites, with the largest occurrence of double tropopauses taking place in north-western India. Events having three or more tropopauses were found at some locations. They were not included due to the very small percentages they represent, the largest of them also occurring in the aforementioned region. This is the reason some percentages in Table S2 do not add up to 100.

LRT height, pressure, temperature, wind direction and speed, and potential temperature were used in a selection procedure aimed at detecting outliers. A long-term climatology was carried out to obtain monthly means and standard deviations for the variables at each different tropopause. If each variable exceeded the grand-time mean by more than two standard deviation units it was considered an outlier and that tropopause was excluded from the analysis. Table S2 shows the percentages of rejections: on average, they are around 10% and 30% for single and double tropopauses, respectively. Composite time series were built for relocated stations. Single LRT and double LRT's lower tropopause time series were consolidated at each location.

One way to characterize the temperature profile in the vicinities of the upper troposphere/lower stratosphere is the LRT sharpness. It was calculated from significant levels as the difference of the mean temperature gradients between the height of the first detected LRT and 500 m above and below (Wirth, 2000). Given this definition, it might be argued that the number of significant levels restrains the sharpness values. However, the annual values of the Spearman's correlation coefficient (r_S) between the number of these levels and the sharpness do not show a clear pattern either with all the locations considered altogether (Figure S2) or individually (not shown).

Figure S3 shows the annual pressure distribution from LRT at two stations with distinct regimes. Bimodality occurs at Patiala (station 42101; 30°19′48″N, 76°27′36″E), with a primary (secondary) maximum at 100 hPa (220 hPa). If only single events are considered the percentages for the secondary maximum decreases in favor of the primary ones. At Thiruvananthapuram (station 43371; 8°28′48″N, 76°56′60″E) the distribution is unimodal irrespective of the inclusion of double LRT events, suggesting single LRTs are by far most frequent at lower latitudes. Unimodality may also be due partly to the inability of the WMO definition to capture the intricate structures of multiple tropopauses in the Tropics (Mehta *et al.*, 2011) and partly due to early balloon bursts before reaching the second tropopause (Seidel *et al.*, 2001; Yuchechen *et al.*, 2010). Separately, LRTM height, pressure and temperature were obtained from mandatory levels (Appendix S1). The aforementioned selection procedure was carried out on these three LRTM variables. In general, detection percentages are quite similar to the single LRT ones (Table S2).

3. Results

Annual, summer and winter LRT mean pressures are shown in Figure S4. Annual values south of 25°N are slightly above the 100-hPa reference for the tropical tropopause (Holton *et al.*, 1995); north of this latitude pressures increase, with highest values (i.e. lowest tropopauses) occurring at the northwest portion of the study region. The wet (summer) and dry (winter) seasons span from June to September (Ding and Sikka, 2006) and from November to February (Chang *et al.*, 2006), respectively. LRTs are higher in the north during summer. Given that the tropopause can be broadly associated to the temperature of the troposphere underneath (Schneider, 2007), the surface temperature in particular (Thuburn and Craig, 1997), results are in agreement with a reversal of the temperature gradient (i.e. directed southwards) created by the large heating of the Tibetan Plateau in during the summer season (Ding and Sikka, 2006). In winter, LRT pressure is lower than (higher than) the annual mean in the southern (northern) portion of the domain.

The LRTM method finds a single tropopause that may correspond either to the single LRT or to the lowest one in multiple LRT events (cf. Figure S3(a)). The differences between LRTM and LRT were calculated for height (z), pressure (P) and temperature (T) during the entire year as well as for the summer and winter seasons. Significances were evaluated using the test for differences of mean for paired samples (Wilks, 2006) with a level of confidence of 95%. Annual, summer and winter long-term means and standard deviations (SDs) for $z_{\mathrm{LRTM}} - z_{\mathrm{LRT}}$ are shown in Figure 1. Annual means are significant and negative except at Srinagar where $z_{\mathrm{LRTM}} > z_{\mathrm{LRT}}$. Summer and winter replicate the annual picture, with a statistically indistinguishable difference at Srinagar in summer. As to SD, it increases northwards in all three cases, with a maximum meridional gradient in winter. This may be attributable to the greater baroclinicity impinged by the westerly

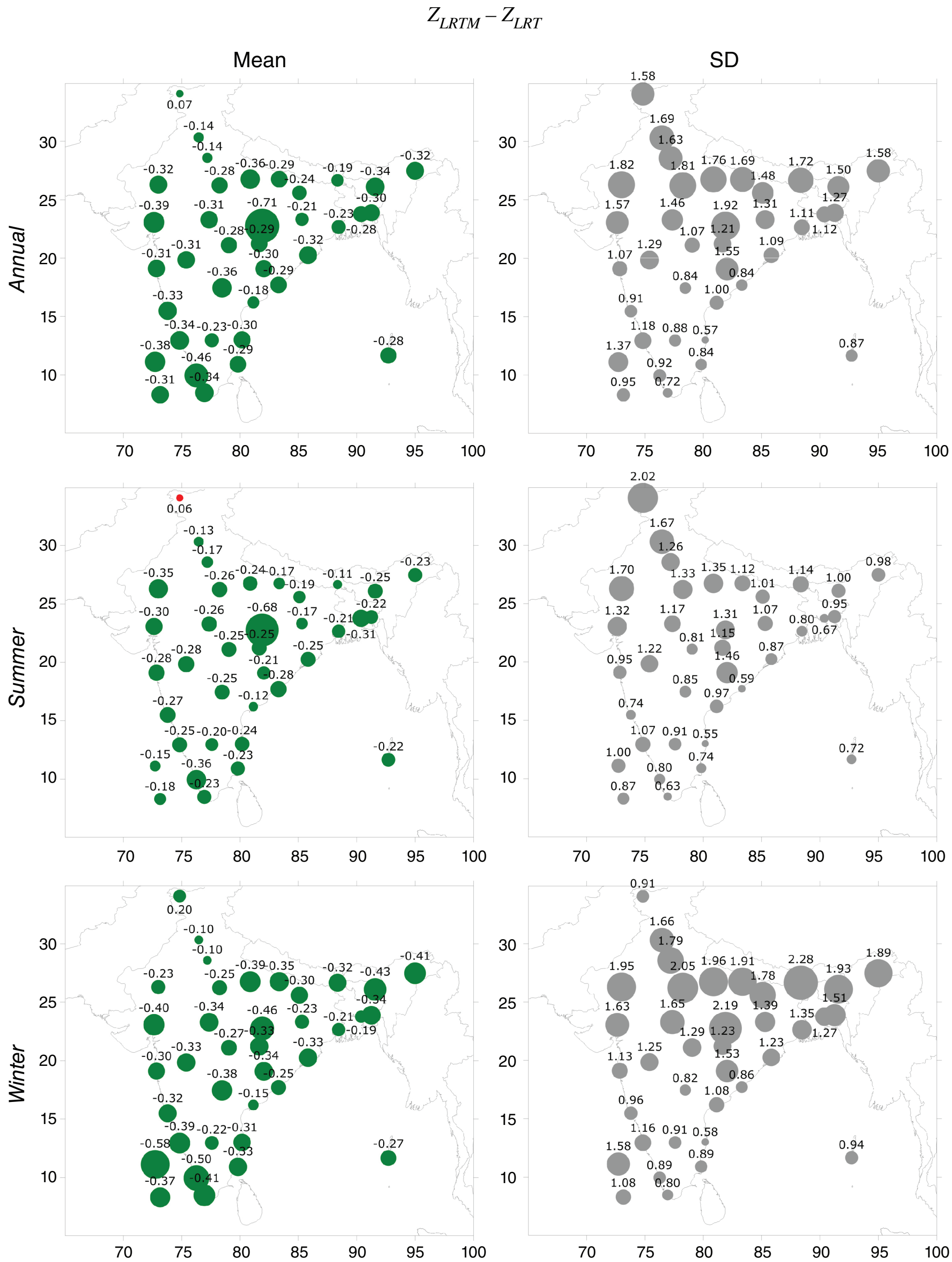

Figure 1. Long-term annual, summer, and winter means and standard deviations (SDs) for $z_{\mathrm{LRTM}} - z_{\mathrm{LRT}}$ (in km). Green (red) dots marks significance (no significance); the size is proportional to the variable's absolute value.

subtropical jet (STJ). In summer it migrates to higher latitudes (Yanai and Wu, 2006). It is in this season when Srinagar experiences the largest SD (above 2 km) between the compared seasons. Significance implies LRTM and LRT averaged values are statistically distinguishable. Notwithstanding, the large SDs at Srinagar indicate that no significance does not necessarily mean individual values are close to one another at any particular time.

Annual, summer and winter means for $P_{\mathrm{LRTM}} - P_{\mathrm{LRT}}$ and $T_{\mathrm{LRTM}} - T_{\mathrm{LRT}}$ are shown in Figure 2. When $P_{\mathrm{LRTM}} - P_{\mathrm{LRT}}$ annual values are considered a significant negative difference occurs at Srinagar only; at the rest of the stations the value is positive, with both variables being statistically indistinguishable at Patiala and Siliguri only. Discrepancies are generally smaller in summer at most of the stations; $P_{\mathrm{LRT}} > P_{\mathrm{LRTM}}$ just at Srinagar, with a separation between the two variables greater than in the annual case, no significance occurring at seven locations, and significance taking place elsewhere. Most stations experience the largest discrepancies in winter, in agreement with Reichler *et al.* (2003). Like in the annual and summer cases, Srinagar is the only location that has a significant negative difference. Six

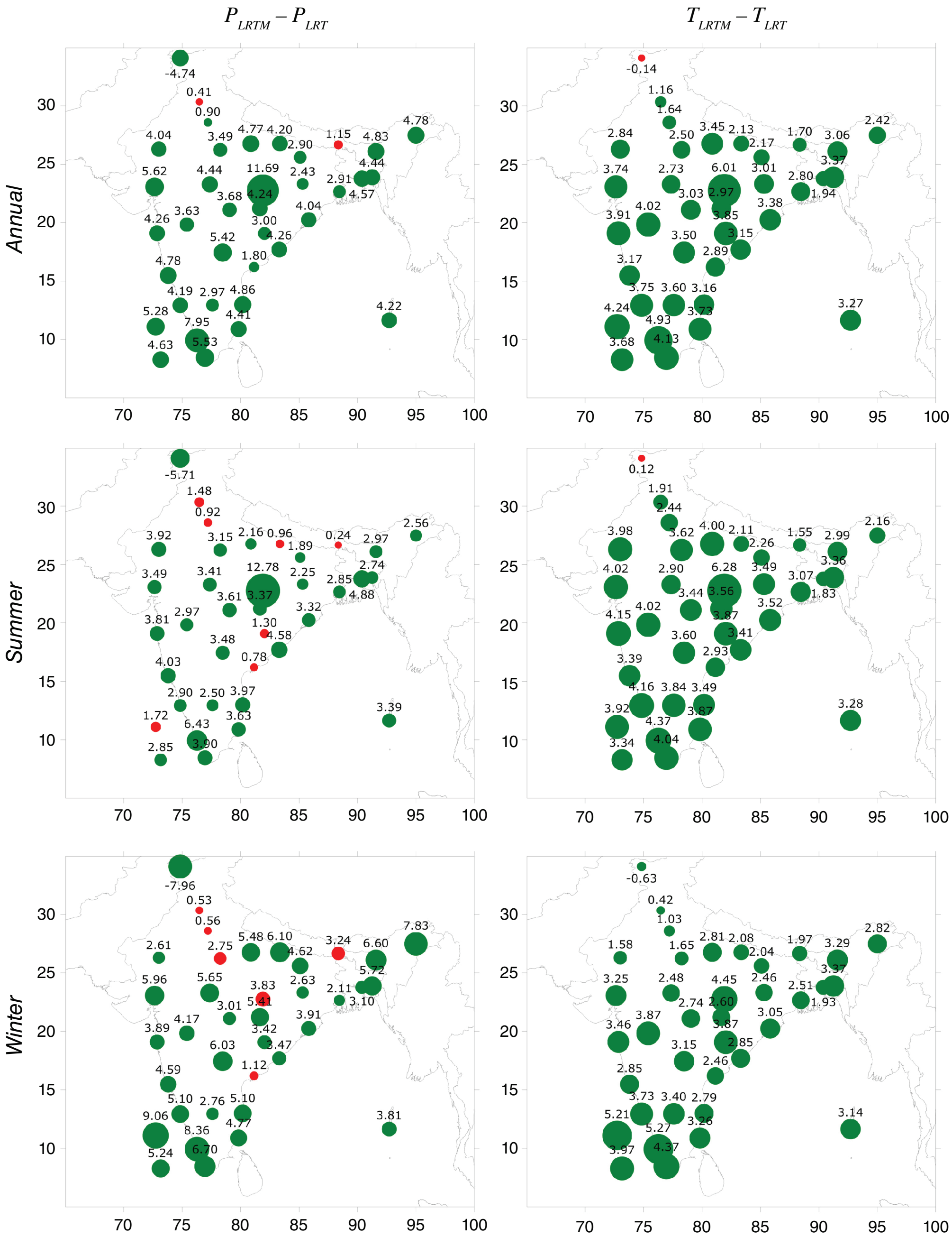

Figure 2. Long-term annual, summer and winter means for $P_{\mathrm{LRTM}} - P_{\mathrm{LRT}}$ (in hPa) and $T_{\mathrm{LRTM}} - T_{\mathrm{LRT}}$ (in °C). Size is proportional to the variable's absolute value. Color code as in Figure 1.

stations have their pressures indistinguishable from each other, and the rest of the sites have a significant positive difference. Overall, results match the inverse relation between pressure and height. The average summer and winter difference SDs are 27 and 36 hPa, respectively, with mean individual values increasing northwards in both seasons but being no greater than 67 hPa anywhere (results not shown). These figures are also in line with those of Reichler *et al.* (2003) for the subtropics.

The annual means for $T_{\mathrm{LRTM}} - T_{\mathrm{LRT}}$ reveal a warm bias at all but one of the stations, with largest values in the southernmost tip of the subcontinent. Similarly, all but one of the values are significant. Summer shows a warm bias too but at all of the locations, with an overall increase of the values with respect to the annual case. Regarding significance, the summer configuration parallels the annual one. Concerning winter, all values are significant, with Srinagar distinguishing itself from the rest of the sites with its cold bias. In general, differences are smaller than in the annual case at all but the southernmost stations, whose values exhibit the largest discrepancies between the compared seasons.

Since remarkable differences exist between the two tropopauses, LRTM cannot be directly used as a replacement for LRT (to fill missing data, for instance), except at a reduced number of stations, during specific seasons, depending on the variable considered and, most importantly, on its variability. The long-term annual, summer and winter values of r_S were calculated

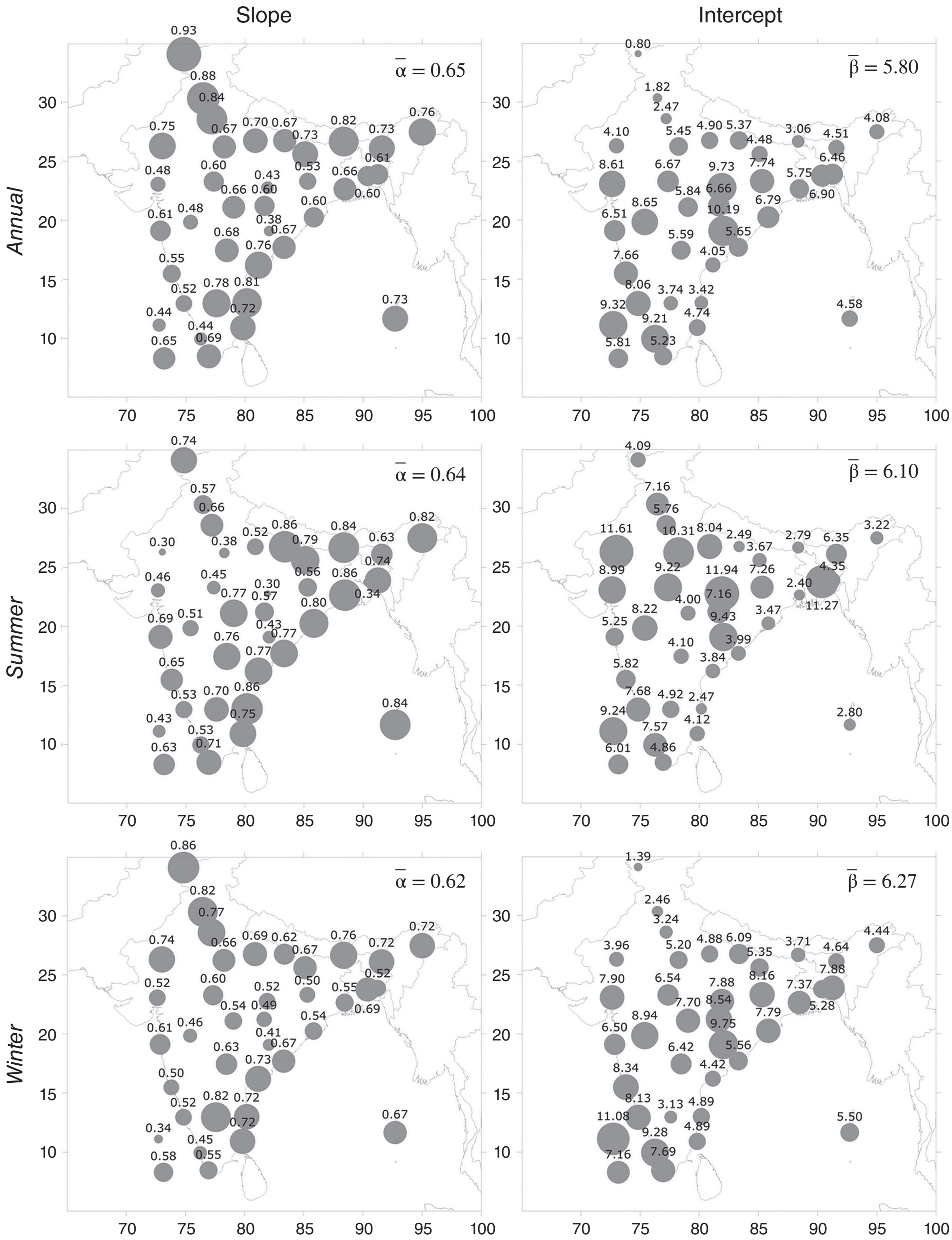

Figure 3. Slope (α) and intercept (β) for the retrieval of the tropopause height from z_{LRTM} with a linear function. Size is proportional to the variable's value. The mean values over all the stations are shown in the upper right corner of each panel.

between each variable's two time series. Given that r_S operates onto the ranks of the series (Wilks, 2006), it is preferred, for the purposes of the paper, over the Pearson's correlation coefficient, as joint behaviors are better represented. Figure S5 shows the long-term annual, summer and winter values of r_S for P. All of them are positive and 95% significant. Results are similar for z and T (not shown). Considering the positive values of r_S, the use of any monotonic function that relates LRT variables with the corresponding LRTM ones is warranted. A linear function $x_{LRT} = \alpha\, x_{LRTM} + \beta$, where x denotes any of the analyzed variables, is preferred for its simplicity, and used in a point-by-point fitting of the data to obtain the dimensionless slope α and the intercept β that correct the value of the LRTM variable to the LRT one. Positive r_S values indicate a direct relationship between the correlated variables, so $\alpha \geq 0$. With all the pairs considered altogether, no bias exists between corresponding LRTM and LRT variables if $\alpha = 1$ and $\beta = 0$, whereas $\alpha = 0$ represents the maximum uncorrelatedness. These two extreme situations help interpreting the results, since the greater the value of α the smaller the uncorrelatedness given that the independent LRTM variable is given more weight.

The values of α and β for z for the annual, summer and winter cases are shown in Figure 3. In all cases α is positive and less than unity and its value is inversely related to β. Maximum values for α occur in the north-western portion of the study region, the region

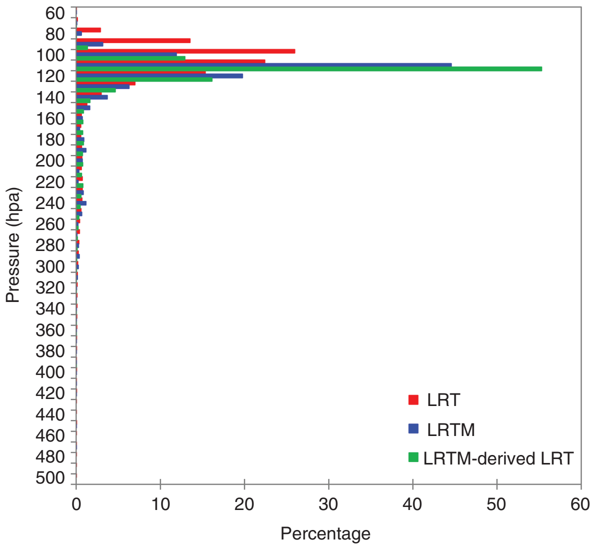

Figure 4. Annual pressure distributions from LRT, LRTM and LRTM-derived LRT over all the stations.

with maximum r_S values for the variable (not shown). Both α and β being positive is in agreement with the condition $z_{LRT} > z_{LRTM}$ at all stations, even at Srinagar where year-round averages show the inverse condition, possibly related to the number of double LRT events at the site, i.e. a greater variability for the difference due to cases with the lower tropopause being considerably low. Summer differs from the annual conditions in that most of the stations have a greater (smaller) $\alpha(\beta)$, in compliance with a reduction of both the mean difference and the variability (cf. Figure 1). The big picture reverses in winter, when both the difference and the SD are, in general, the largest between the compared seasons.

Comparisons between different variables can be made through α given its dimensionless character. Generally speaking α year-round values for P (Table S3) are slightly smaller than for z, thus increasing the uncorrelatednesses. For summer, α generally takes on greater (smaller) values than for the entire year at most of the stations south (north) of 20°N, thus increasing (decreasing) the correlatedness with respect to the annual case. Approximately the inverse situation takes place during winter. Regarding T, α annual values are the smallest between the analyzed variables and they generally decrease during summer (Table S4), making summer uncorrelatednesses greater than the annual ones. Changes in α for winter are not as noticeable as with the other two variables: they are close to the annual values at most of the stations. In a winter versus summer comparison α generally decreases south of 20°N. All α values are significant at a 95% confidence level. Annual, summer and winter β values for P and T are also included in Tables S3 and S4, respectively. The annual pressure distribution from LRT, LRTM and LRTM-derived LRT is shown in Figure 4.

Figure 5 shows the root mean square (RMS) for the discrepancy between z_{LRT} and the one linearly calculated using z_{LRTM} for the annual, summer, and winter cases. Assuming that there exists a dependence between $z_{LRTM} - z_{LRT}$ and the LRT sharpness, it also shows the values of r_S for the correlation between both variables. RMSs generally increase northwards, year-round as well as in summer and winter, whereas the values of r_S show that the LRT sharpness dependence decreases with latitude. During summer, RMSs are larger in the north-westernmost stations, in coincidence with a monsoon trough located there. Notwithstanding, the largest RMSs occur during winter in the 25°–30°N belt, in agreement with both the southernmost position of the STJ and the northwest-by-southeast ridge corridor in the region (Ding and Sikka, 2006). The behaviors for P and T (Figures S6 and S7, respectively) parallel the one described for z, with T having the strongest inverse dependence with latitude in winter.

4. Summary and concluding remarks

Differences between tropopauses calculated from mandatory levels (LRTMs) and WMO-defined lapse rate tropopauses (LRTs) at 37 upper-air stations spanning the Indian subcontinent's tropical and subtropical latitudes have been analyzed for height (z), pressure (P) and temperature (T), focusing on a 42-year annual, summer and winter means. Results indicate that LRTM is lower than LRT at all the stations with the exception of Srinagar, which is located in a region where the occurrence of multiple LRTs is relatively high all year long. In general, $|z_{LRTM} - z_{LRT}|$ shows a decrease in summer with respect to annual conditions at all the stations, whereas the separation between both tropopauses increases during winter. P behaves in much the same way. As for $T_{LRTM} - T_{LRT}$, there is an overall increase in summer with respect to annual conditions; in winter, lesser values occur with the exception of the southernmost stations, whose differences are even greater than in summer. Significance for the differences were also addressed.

Results indicate that the use of LRTM as a direct replacement for LRT is discouraged. However, significant positive Spearman's correlations show that they are related so LRT variables can be estimated from LRTM ones. The station-specific slope and intercept for a linear function linking the variables were obtained for the annual, summer and winter cases. To the best of our knowledge, results here are the first ones including double tropopauses in the comparisons [they were not considered in Reichler *et al.* (2003) and Zängl and Hoinka (2001)]. Largest RMSs occur in winter and seem to be connected to anticyclonic anomalies. However, the absolute values of the winter correlations between the LRT/LRTM discrepancy and the LRT sharpness (Figures 4, S6, and S7) are the lowest ones, an indication that the sharpness may not play a fundamental role in establishing the differences. This is a matter of future investigation, as also is the possibility of calculating multiple tropopauses from the LRTM method. One of the utilities of this work is the direct retrieval of LRTM variables from fixed pressure levels

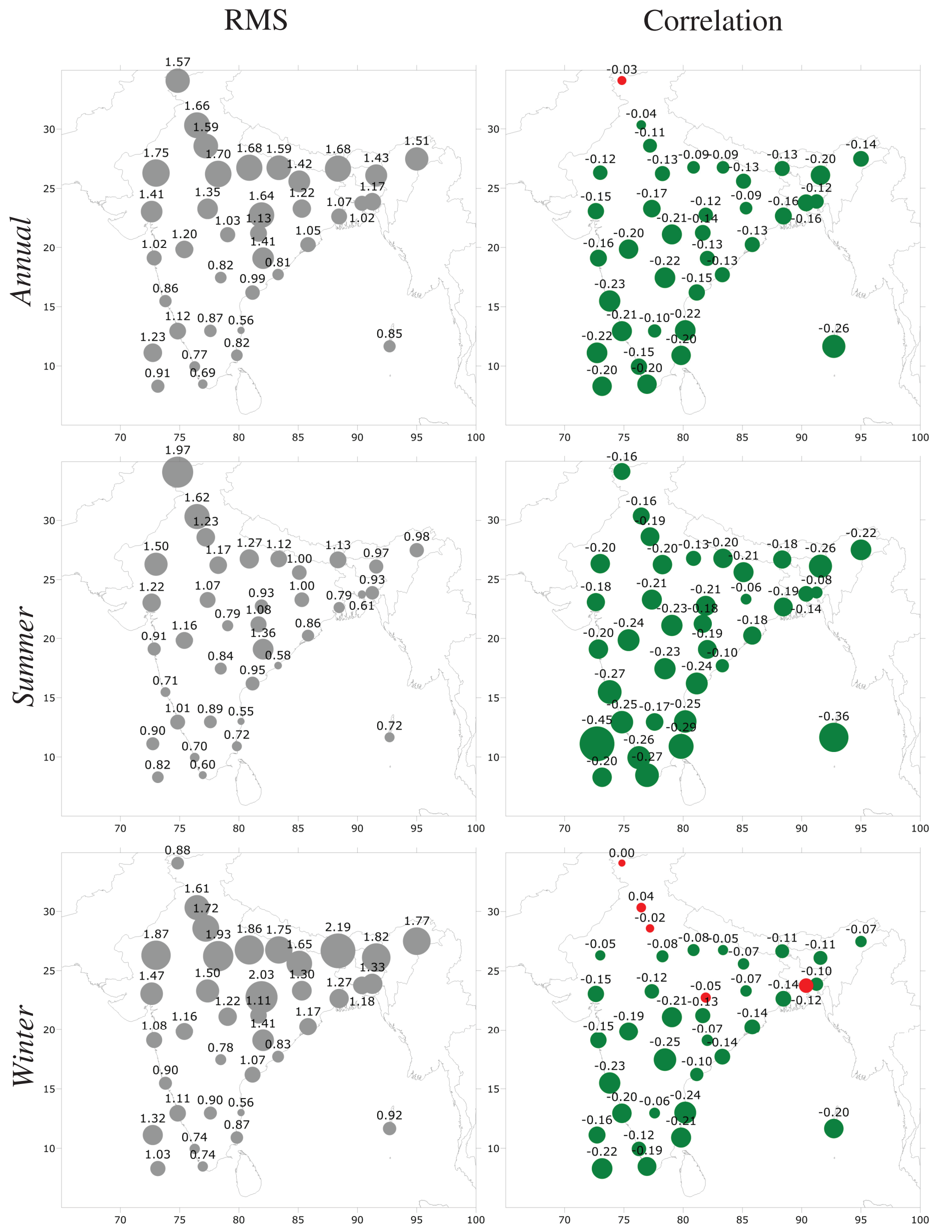

Figure 5. Root mean squares (RMS) for the difference between z_{LRT} and the tropopause height calculated from z_{LRTM}, and Spearman's correlations between $z_{LRTM} - z_{LRT}$ and the LRT sharpness. RMS values in km. Color code for correlations as in Figure 1.

for worldwide regions where radiosonde launchings are scant and, on the other hand, to use them as a proxy for LRT variables in a variety of applications, such as variability studies or anthropogenic effects in the troposphere through trends. It is worth emphasizing that the only requirement for the method in order to make comparisons between the tropopauses retrieved with it is that it should be used on fixed pressure levels, i.e. mandatory levels, or model levels whenever possible.

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Supporting information

The following supporting information is available:

Appendix S1. Calculation of thermal tropopauses from mandatory levels and supplemental figures and tables.

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