Climatological features of global multiple tropopause events

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[1] This study examines various climatological features related to multiple tropopause events (MT events). The analysis is based on the lapse rate definition of the tropopause and is performed on a radiosonde data subset taken from the Integrated Global Radiosonde Archive database. The global statistics of MT events are analyzed, taking into consideration both their seasonal and geographical variations. Our results are in moderate qualitative agreement with those of earlier studies. They reinforce the analytical findings of other researchers, but at the same time highlight important differences in both the number and position of the maximum occurrence of MT events. We found a latitudinal band of multiple tropopause occurrence in the Northern Hemisphere and three centers in the Southern Hemisphere, which coincided with identified zones of maximum cyclogenesis. The climatological features of pressure, temperature, and vertical separation of MT events revealed the complexity of these phenomena, which behave very differently according to latitude and season.

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1. Introduction

[2] The tropopause is defined as the boundary between two very different atmospheric layers; namely, the turbulently mixed troposphere and the stratosphere, which is a more stable stratified layer. It is therefore extremely sensitive to changes in the thermal, dynamic, and chemical structure of the atmosphere [*Highwood and Hoskins*, 1998; *Hoinka*, 1998; *Seidel et al.*, 2001]. This transition from the troposphere to the stratosphere is marked by rapid changes in the dynamical, thermal, and chemical properties of the atmosphere, such as changes in lapse rate, potential vorticity [*Hoskins et al.*, 1985], or chemical characteristics [*Bethan et al.*, 1996]. The study of the tropopause is important at different temporal and spatial scales. At microscales and mesoscales, it is important because the tropopause represents the limits of tropospheric convection. At the synoptic scale, it is important in the development of large weather systems because the growth of weather systems involves the interaction of waves that propagate on temperature gradients at the tropopause [*Davies and Bishop*, 1994]. At climatic scales, different observations have indicated that the height of the tropopause may have increased since 1979 [*Sausen and Santer*, 2003; *Santer et al.*, 2003a] as a consequence of cooling in the stratosphere caused by ozone loss and warming in the troposphere caused by greenhouse gases [*Santer et al.*, 2003b]. Associated with a layer of strong increase of static stability, the tropopause plays a crucial role in the exchange between the troposphere and stratosphere. Such exchanges influence the reduction of stratospheric ozone, tropospheric pollution, and global warming. Furthermore, recent observations have provided strong evidence that the stratosphere may modulate the tropospheric climate in association with annular modes [*Baldwin and Dunkerton*, 1999, 2001; *Thompson et al.*, 2002].

[3] Despite the abundance of previous work on this topic, significant uncertainty remains in many areas. In a recent article, *Gettelman et al.* [2007] highlighted some of the important gaps in our knowledge of the tropopause. The major issues concern (1) the explanation of the existence of the tropopause itself, (2) the role that climate models could play in understanding both the impact of climate change on the tropopause and vice versa, and (3) the need for a deeper understanding of the structure of the upper troposphere and lower stratosphere (UTLS) in order to gain a more complete knowledge of the exchange processes involved.

[4] The precise location of the tropopause can be defined in a variety of ways, according to the dynamic, thermal, and chemical properties of the atmosphere. The formal definition of the tropopause adopted by the World Meteorological Organization (WMO) in 1957 is a thermal definition based on lapse rate. The tropopause that results from applying this definition is called the "lapse rate tropopause."

[5] Using the WMO definition, it is possible to find, in a single sounding, multiple stable layers that fit the criteria for tropopauses. Occurrences of such multiple stable layers have been described as "multiple tropopause events" (hereafter

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MT events) and were first described as such by *Schmauss* [1909]. Recently, there has been considerable interest in the relevance of MT events for understanding the exchanges between the stratosphere and troposphere. During 2006 and 2007, three global climatologies of MT events were published, the first derived from Global Positioning System (GPS) radio occultation by *Schmidt et al.* [2006], the second by radiosonde data by *Añel et al.* [2007], and the most recent by *Randel et al.* [2007] based on radiosondes, reanalysis, and GPS radio occultation. The use of reanalysis data in studies of multiple tropopauses must always be checked and cross referenced using other techniques, owing to the low vertical resolution and attendant biases of the reanalysis. The radiosonde retrievals are still the principal source of information regarding the thermal structure of the troposphere, tropopause, and lower stratosphere. These retrievals are still the primary source of validation of GPS retrievals, other satellite techniques, and reanalysis products. For this reason, radiosondes continue to be the most important data sources for determining tropopause parameters from a climatic perspective [*Randel et al.*, 2000].

[6] In the study reported herein, we sought to achieve a sound observational characterization of MT events, using the most comprehensive and largest radiosonde data set compiled to date; namely, the Integrated Global Radiosonde Archive (IGRA). This study is an extension of the previous work by *Añel et al.* [2007] in which only global statistics of multiple tropopauses were studied without considering seasonality or geographical distribution.

2. Data and Methodology

[7] We analyzed meteorological sounding data contained in the IGRA [*Durre et al.*, 2006] corresponding to 0000 and 1200 UTC in the period 1965 to 2004. This period contains the most common sounding times for all the stations. Given that the number of stations releasing sondes at other times may be appreciable, we grouped as 1200 UTC those soundings that correspond to launchings between 0900 UTC and 1500 UTC. For 0000 UTC, we used the interval from 2100 UTC to 0300 UTC.

[8] The analysis was based largely on an initial subset of 187 stations (hereafter S187) (see auxiliary material), which is the same as that used previously by *Añel et al.* [2007].[1] However, the station with WMO code 93072 was removed, owning to the relatively short duration of its series.

[9] The tropopause and MT events were computed for S187, using the WMO lapse rate definition [*World Meteorological Organization*, 1957]:

[10] "(a) The first tropopause is defined as the lowest level at which the lapse rate decreases to 2°C/km or less, provided also the average lapse rate between this level and all higher levels within 2 km does not exceed 2°C/km.

[11] (b) If above the first tropopause the average lapse rate between any level and all higher levels within 1 km exceeds 3°C/km then a second tropopause is defined by the same criterion as under (a). This tropopause may be either within or above the 1 km layer."

[1]Auxiliary materials are available at ftp://ftp.agu.org/apend/jd/2007jd009697.

Figure 1. Stations remaining in the studied subset after applying the homogenization procedures to S187.

[12] In order to avoid unreal tropopause detections, those cases with first tropopause pressures greater than 500 hPa were removed. The geopotential height was calculated by integrating the hydrostatic equation in the "ln p." In a small percentage of cases (9% of all the levels for all the soundings used) when pressure data were not available but geopotential height data were present for the respective level of the sounding, the pressure was retrieved inverting the integrated hydrostatic equation. Hereafter, we use LRT1, LRT2 and LRT3 to denote the first, second, and third lapse-rate tropopauses. We use the following nomenclature: detection of only LRT1, a single tropopause event (ST); detection of LRT1 and LRT2, double tropopause event (DT); and detection of LRT1, LRT2, and LRT3, triple tropopause event (TT).

[13] In order to ensure that the obtained results were representative and that all the soundings used were comparable and had the same chance to detect LRT1, LRT2, and LRT3, we determined what soundings we would deem to be valid. We only considered those soundings that reached the 50 hPa pressure level over tropical regions (30°N–30°S) and 70 hPa over the extratropics (30°N–60°N and 30°S–60°S) and poles (60°N–90°N and 60°S–90°S). The limits of 50 hPa and 70 hPa are based on the fact that they correspond to typical pressure values for LRT3 as obtained by *Añel et al.* [2007]. Another condition that was imposed on the data was to retain only those soundings that had at least one level in the intervals defined by the following consecutive pressure values: 450 hPa, 350 hPa, 250 hPa, 175 hPa, 125 hPa, and 85 hPa.

[14] This condition was imposed to ensure the existence of at least one level with valid data in the vicinity of the mandatory pressure levels: 500 hPa, 400 hPa, 300 hPa, 200 hPa, 150 hPa, 100 hPa, 70 hPa, and 50 hPa.

[15] We considered a station to be valid only if it had at least three valid decades, where a decade (categorized as 1965–1974, 1975–1984, 1985–1994, and 1995–2004) is valid only if it contained at least five valid seasons for a given season, and a season (categorized as DJF (December/January/February), MAM (March/April/May), JJA (June/July/August), SON (September/October/November)) is valid only if it contained at least 30 days with a valid sounding. Figure 1 shows all the valid stations for at least one season. Table 1 lists the stations that passed the validation criteria only for some seasons.

Table 1. Stations That Passed the Validation Criteria Only for Some Seasons[a]

WMOcode	Seasons
08522	JJA, SON
20107	MAM, JJA
43003	MAM, JJA, SON
63985	SON
68424	DJF
70454	MAM
81405	JJA, SON
82332	JJA
89009	DJF, MAM, SON
89542	DJF
89564	DJF, MAM
89664	DJF, SON

[a]Such seasons are indicated in the right column.

[16] The statistics were based on the conventional means of the seasons (DJF, MAM, JJA, SON). To obtain meridional profiles, we calculated zonal means for 10° wide latitudinal bands. It is worth noting that between 80° and 90°, there is only one station in each hemisphere. Therefore, care was required when analyzing the results in these zones because of the scarcity of data.

3. Results

3.1. Global Occurrence of MT Events

[17] As our main focus is on the occurrence of MT events, we begin by showing the spatial distribution of the frequency of their occurrence. Figure 2 shows the seasonal mean frequency of DTs and TTs, normalized to the respective seasonal mean frequency of LRT1 computed for our subset (the frequency of MT events is given as a percentage with respect to the number of LRT1 events). The normalization by LRT1 is intended to be an indirect control of the quality of the soundings, because it was assumed that LRT1 must always exist. However, we are aware that this assumption may not always be verified over the polar caps. All the stations in S187 present several MT events, which is coherent with previous findings by *Añel et al.* [2007]. This result suggests a

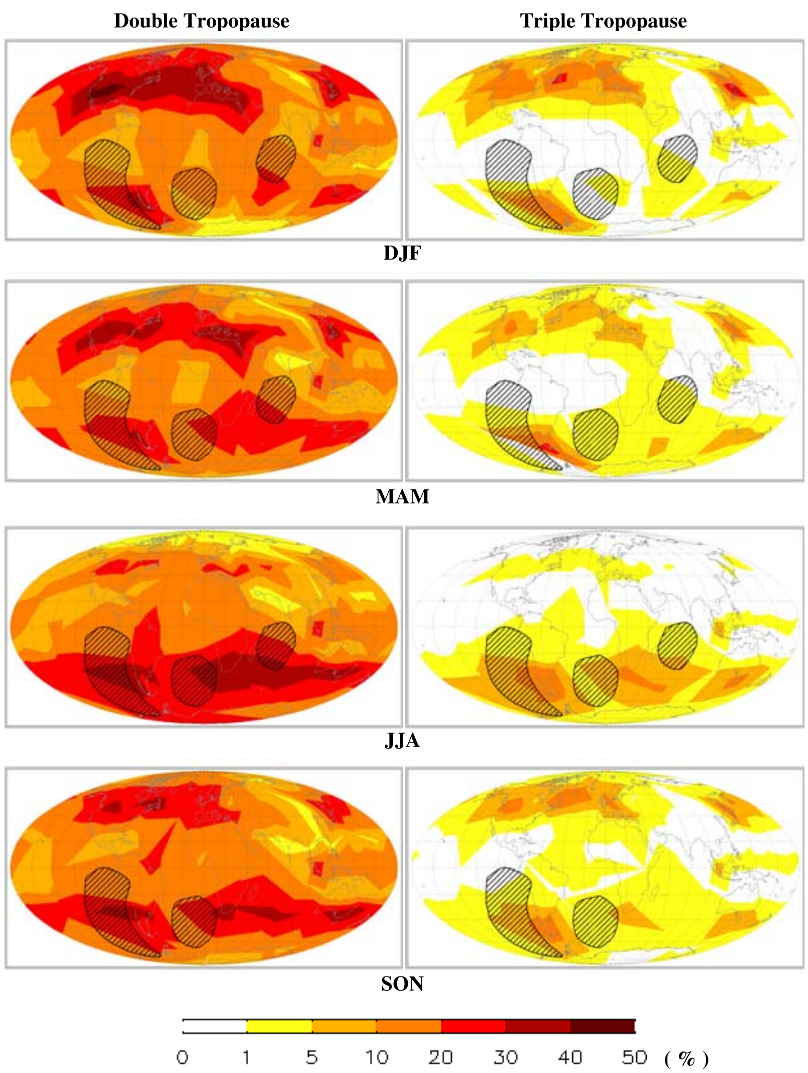

Figure 2. Percentage of seasonal mean of (left) DT and (right) TT occurrences with respect to the seasonal mean of LRT1. The shaded regions mark the zones where the results could be affected by the interpolation because of the lack of stations.

more frequent occurrence of MT events than the frequency obtained by *Seidel and Randel* [2006] and *Randel et al.* [2007], which reported very few or no MTs in some stations.

[18] The relative spatial distribution of MT events as described above shows a clear maximum located in the midlatitudes (30°N–40°N and 30°N–40°S), near the subtropical jet stream region, reaching maximum values during the hemispheric winter and minimum values during summer. In the NH, the difference between DJF and JJA is around 20% for both DT and TT, while the SH has a more homogeneous temporal distribution. This result is in agreement with the known higher seasonal variability of the NH.

[19] In the NH latitudinal band of high MT occurrence, maxima over the center and east coast of the USA, the Mediterranean Sea, and Japan may be discerned. The typical percentage values in these zones for DJF are 40–50% for DT and 10–20% for TT. In the SH, three maxima can be observed over the Strait of Magellan, South Africa, and Tasmania/Southern Australia with similar winter percentages to those observed in the NH. These results mostly agree with the analysis by *Randel et al.* [2007], who performed a similar analysis using GPS data, the main differences being found mainly in the frequency of MT events in DJF over Tasmania/Southern Australia.

[20] The maximum percentages of MT events that occur near the subtropical jet stream regions agree with the results of *Randel et al.* [2007], who attribute the MT events to latitudinal migration of the tropical tropopause over the extratropical one. However, there is another striking feature: the extreme spatial coincidence between the observed distribution of MT maxima, in Figure 2, and the pattern of seasonal cyclogenesis climatology obtained by *Wernli and Schwierz* [2006]. It is also worth mentioning the resemblance of the distribution of MT maxima to the occurrence of cutoff low systems obtained by *Nieto et al.* [2005] for the NH and *Fuenzalida et al.* [2005] for the SH. In a previous study, *Wirth* [2001] found a clear connection between the upper troposphere cyclogenesis phenomena and the occurrence of MT events. *Shapiro* [1980] had previously pointed out the relationship between strong upper tropospheric cyclones and the formation of tropopause folds. Those spatial coincidences suggest that the cyclogenesis and the cutoff low mechanisms may be associated with MT occurrences.

[21] Figure 3 shows the intra-annual variation of the number of soundings that met the validation criteria and the number of STs, DTs, and TTs for the tropics, extratropics, and poles. In order to avoid artificial counts of the numbers of soundings for some seasons, because some were lacking as indicated in Table 1, we only used the stations that passed the validation criteria for the four seasons. The results obtained confirm those shown in Figure 2. The shape of the plot of the number of soundings that met the validation criteria is similar to that for the number of STs. We have also calculated the percentage of soundings meeting the validation criteria that have an identifiable LRT1. The minimum was 99.41% so the figure is not shown. For the tropical region, the number of cases does not change significantly throughout the year. However, the extratropics show a strong seasonal variation, with a clear difference in behavior between ST and MT events. For the former, the number of cases is a maximum during the

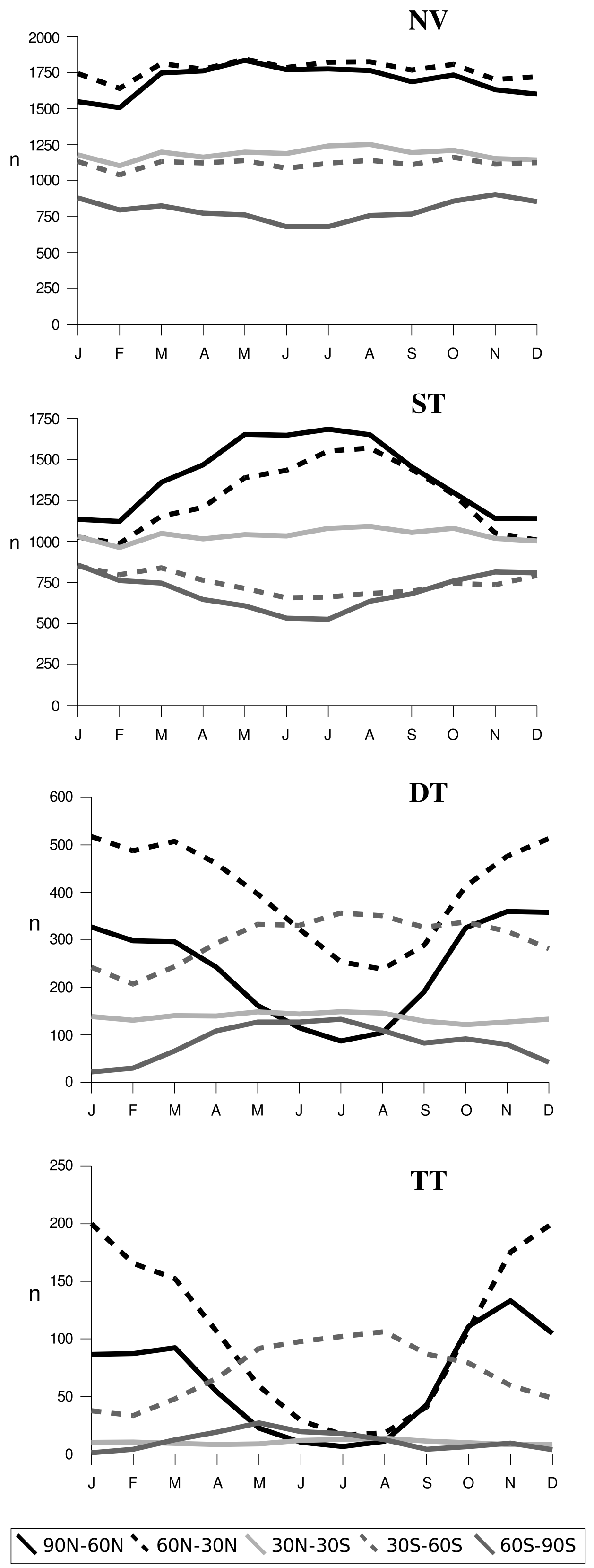

Figure 3. (top to bottom) Intra-annual distribution of the number of soundings meeting the validation criteria (NV) and the number of cases of ST, DT, and TT for tropics, extratropics, and poles.

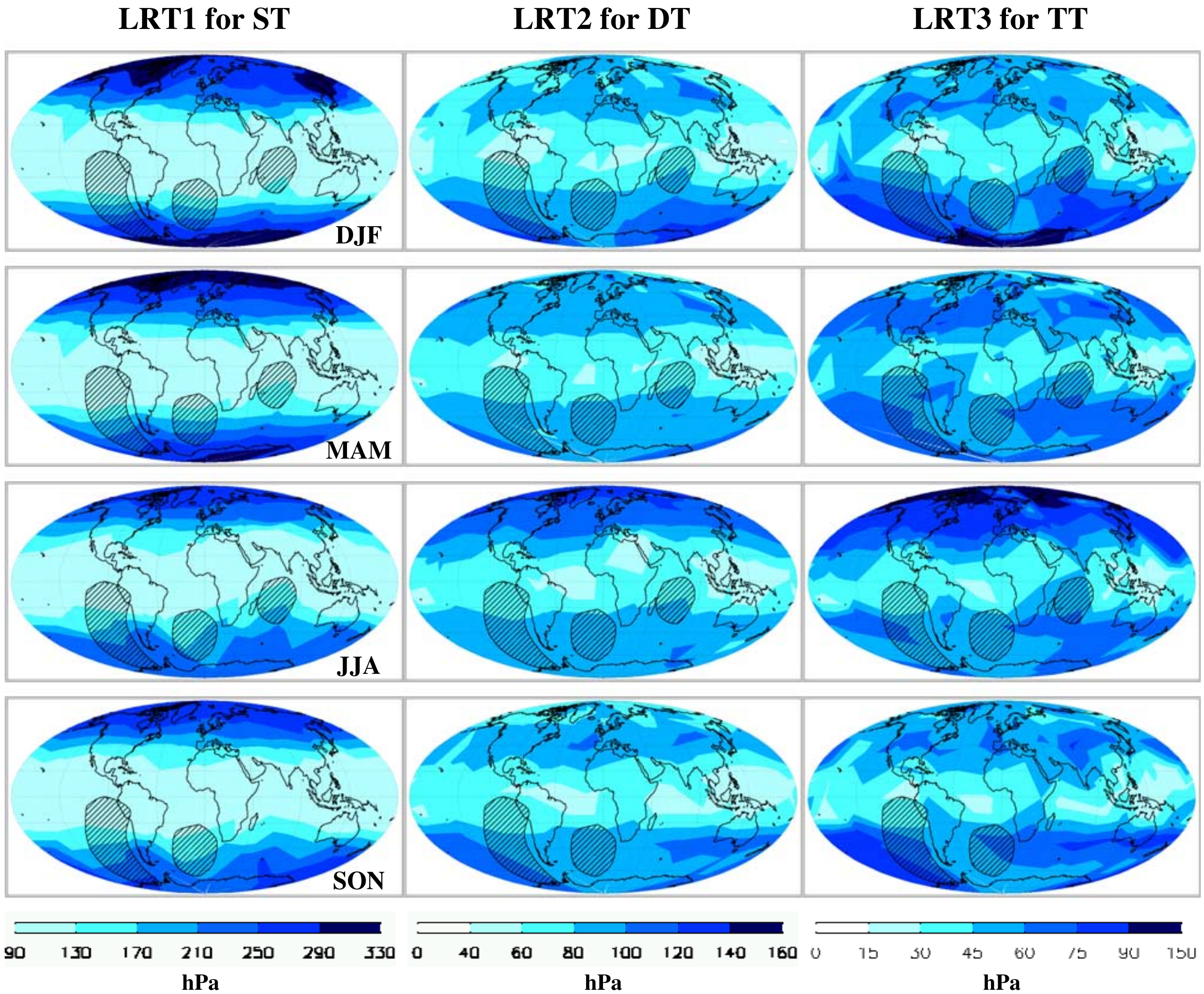

Figure 4. Seasonal mean pressure for LRT1 in the case of ST, LRT2 in the case of DT, and LRT3 in the case of TT. The shaded regions mark the zones where the results could be affected by the interpolation because of the lack of stations.

summer and a minimum during the winter, while for the latter the opposite is true. The polar caps show behavior similar to that in extratropics. The anticorrelation between the seasonal variations of STs and MTs is inherent to the physical meaning of the seasonal cycles. However, it must be take into consideration that the results may be somewhat contaminated by the month-to-month differences in the number of soundings that pass the validation criteria that we stated in section 2.

3.2. Climatology of MT Event Pressure and Temperature

[22] Figures 4 and 5 show the global seasonal mean fields of pressure and temperature, respectively, for the higher lapse rate tropopause detected, that is, for LRT1 in the case of ST, LRT2 in the case of DT, and LRT3 in the case of TT. This is the criterion used for all the results shown in the paper, unless indicated otherwise. As expected, the typical meridional structure of LRT1 is observed, with the pressure ascending from the tropics to the poles. The existence of persistent relative maxima of pressure of LRT1, LRT2 and LRT3 in the NH extratropics over the zones coincident with the maximum occurrence of MT can be observed. This feature is clear except for JJA.

[23] The structure of the temperature and pressure fields is coherent, with lower temperatures corresponding to lower tropopause pressures, and higher temperatures observed over zones of greater pressure. This relationship seems obvious for STs and DTs, but less so for TTs. According to the results shown, it is a global rule that temperature is greater for TTs than for DTs, and greater for DTs than for STs.

[24] Our results agree with the mean fields of pressure obtained by *Zängl and Hoinka* [2001] for the LRT1 for STs over the polar regions, with respect to both the values and the seasonal variations of the fields. The maximum values of 330 hPa occur over the SH polar cap and the equatorward decays of pressure are almost equal in both cases. For the case of the temperature, it is more difficult to make an assessment using the figures, because the variations of this magnitude over the polar caps are typically not much greater than 5°C.

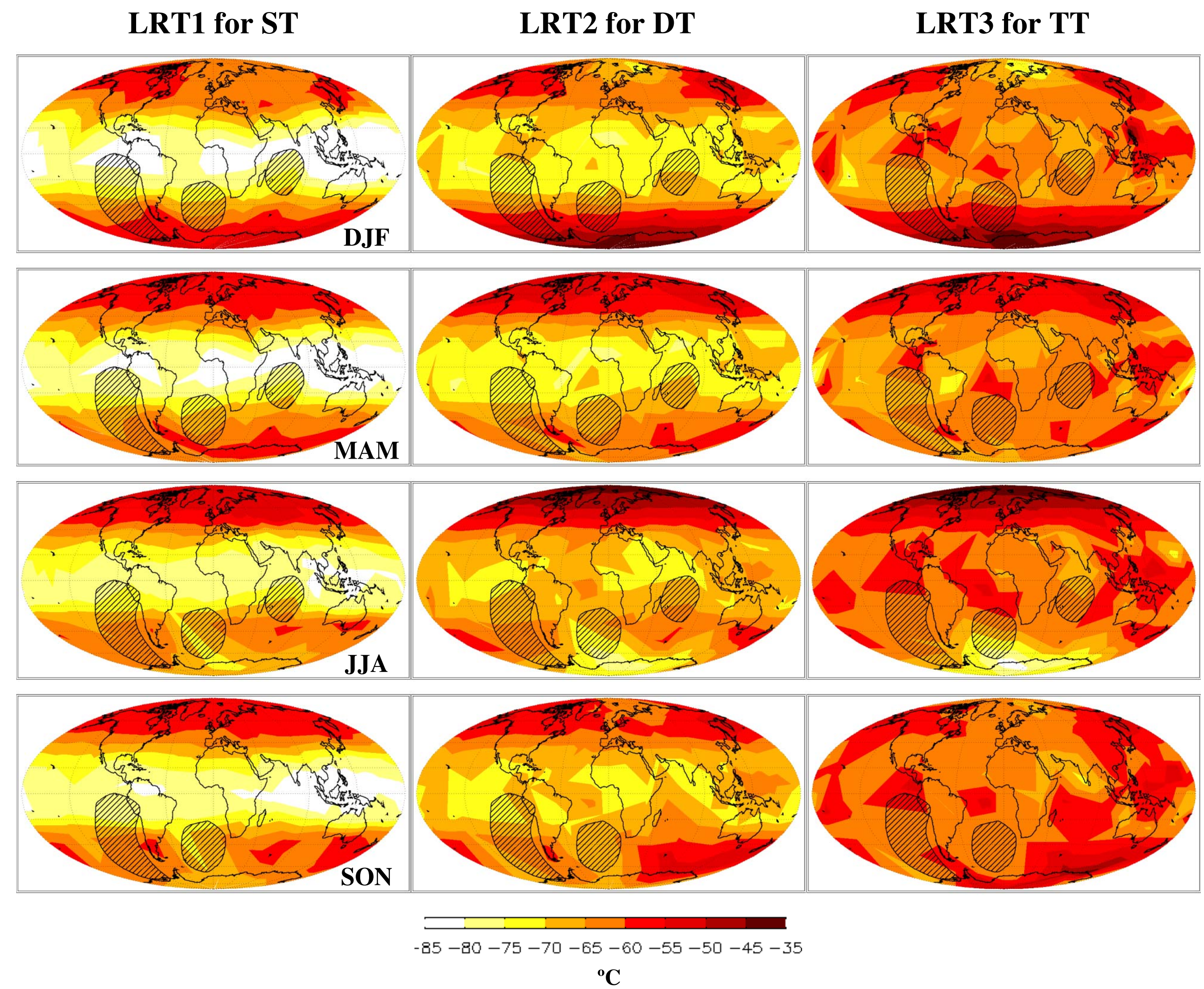

Figure 5. Seasonal mean temperature for LRT1 in the case of ST, LRT2 in the case of DT, and LRT3 in the case of TT. The shaded regions mark the zones where the results could be affected by the interpolation because of the lack of stations.

[25] The polar tropopause is colder for the winter hemisphere, in accordance with the generally understood temperature structure for the stratosphere, with temperatures decreasing from the summer pole to the winter pole [*Brasseur and Solomon*, 2005]. For the case of NH MT events, it is observed that these lower temperature values expand out of the polar latitudes to the extratropics for longitudes between 20°W and 40°E. Moreover, for the case of STs, the results obtained resemble the temperature field previously obtained by *Hoinka* [1999] using reanalysis data.

[26] Figure 6 shows the meridional distribution of pressure and temperature for STs, DTs, and TTs, separately for each season. In the extratropics, the LRT1 pressure for STs is greatest in the hemispheric winter. For both hemispheres, the winter/summer pressure differences range from about 40 hPa to 70 hPa, with the maximum difference located around 40 degrees latitude. This result agrees with the mean altitude profile found by *Randel et al.* [2007] using GPS, except that in their case the pressure over the poles was always greater for DJF than for JJA. However, there is a noticeable difference between the NH and SH. While for the NH, the pressure difference between DJF and JJA is small (only 9 hPa), for the SH this difference is about 100 hPa. Moreover, it is noticeable that maximum pressure values for the NH polar cap are reached during MAM.

[27] The meridional temperature profile for LRT1 for STs resembles the equivalent pressure profile, with greater temperatures corresponding to greater pressures and vice versa. The exceptions are the NH high latitudes, where the observed temperature values are greater during JJA than during DJF, when the pressure is lower. It is worth noting that the small difference between JJA and DJF pressure values at the equator (13 hPa) leads to a temperature difference of around 4°C.

[28] For MT events, pressure and temperature patterns are very similar to those for STs. It is noticeable that the extratropical pressure difference between DJF and JJA is much lower for MT events than for STs. In addition, for MT events, the pressure for NH high latitudes is greater for JJA than for DJF, which is consistent with the observed temperature pattern, although contrary to the one observed for the case of STs.

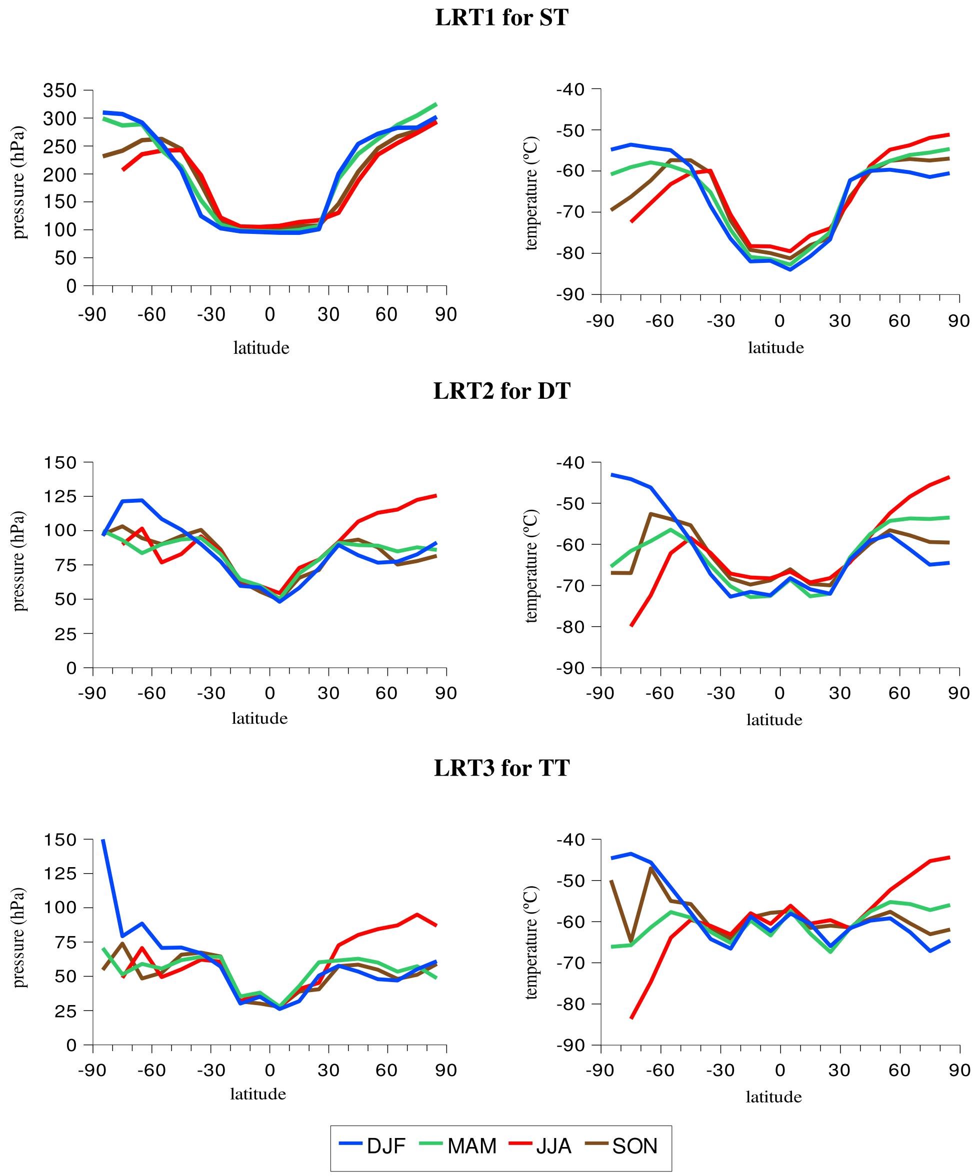

Figure 6. (left) Meridional distribution of pressure for LRT1 in the case of ST, LRT2 in the case of DT, and LRT3 in the case of TT. (right) Same but for temperature.

[29] The profiles for MT events over the Southern polar region should be interpreted with care, owing to the small number of MT events over that region present in the data sets (see Figure 3).

[30] Figure 7 shows the standard deviations of the seasonal means shown in Figure 6. For MT events, similar values are obtained for the tropics and extratropics, although here the relevance of the same magnitude is greater. It is clear that the standard deviation plots are influenced by the number of MT events. The values are greater in the latitudes that have a lower number of MT events. For the same reason, the standard deviation is greater for TTs than for DTs.

[31] Figure 8 shows the intra-annual variation of pressure and temperature for ST and MT events at the tropics, extratropics, and polar caps. The pressure maximum is located in the NH polar regions and occurs during the MAM season. However, the minimum for ST is in JJA, which is coincident with the maximum MT events. The seasonal variation of pressure in the extratropics resembles the pattern previously found by *Varotsos et al.* [2004] over Athens, but with obvious differences in the values because of the contribution of stations in higher latitudes. In the tropical region, the pressure of ST and MT events is lower than for anywhere else in the globe for the whole year and is almost constant. Temperatures in the tropics show behavior similar to that observed for pressure, but with the difference being greater than for the SH pole during JJA in the case of DTs and TTs. In addition, the LRT3 for TTs over the polar regions during the respective hemispheric winter is colder than in the tropics. This structure is also observed in Figure 6 and is consistent with the structure of temperature for the stratosphere.

[32] In order to gain some insight into the structure of the upper troposphere and lower stratosphere, which is an issue for investigation identified in the SPARC tropopause initiative [*Gettelman et al.*, 2007], we analyzed the global

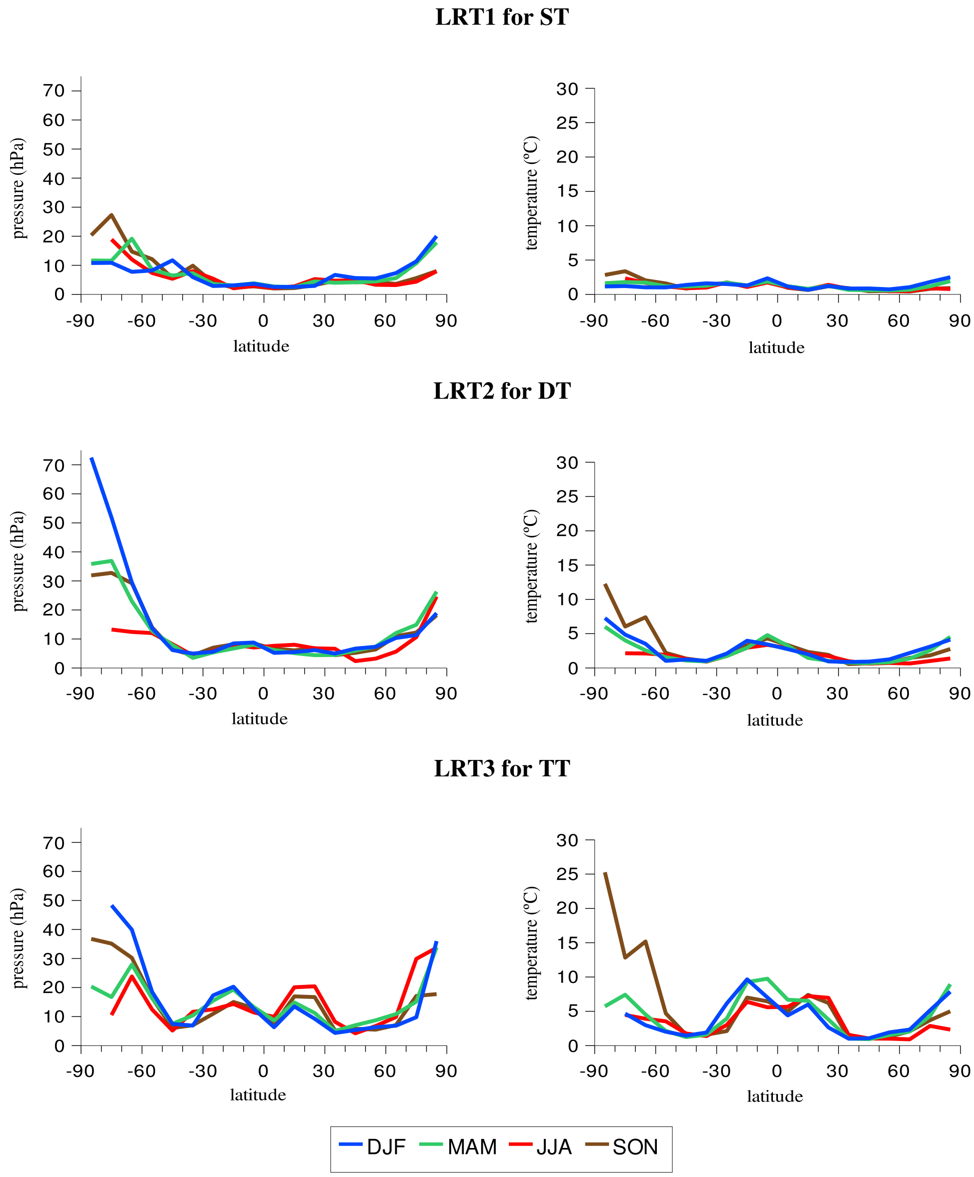

Figure 7. Standard deviation plots corresponding to Figure 6.

seasonal meridional profiles of LRT1 features for the cases of STs, DTs, and TTs, separately. We performed similar analysis for LRT2 in the cases of DTs and TTs (Figures 9 and 10). In general terms, LRT1 pressure (left-hand side of Figure 9) is greater for the case of TTs than for DTs, and greater for DTs than for STs. The greatest differences in pressure are observed between 30°S–60°S and 10°N–40°N. In some cases, this difference is around 100 hPa, and is usually greater for the SH than for the NH. The seasonal differences are more or less constant. The equatorial pressure of LRT1 is very similar for all the three cases (STs, DTs, and TTs), being nearly constant for the whole year, with values from 100 hPa to 120 hPa. However, a clear variation is observed for the SH polar cap with values around 320 hPa for DJF, descending to 200 hPa during JJA. This variation is accompanied by almost constant equatorial temperature (Figure 10) and SH polar temperature ranging from −55°C for DJF to −77°C for JJA. The NH polar cap seems to be about 5°C colder in DJF than in JJA. The corresponding temperature meridional distribution shown in Figure 10 is consistent and generally proportional to the pressure distribution.

[33] For the case of the LRT2 pressure (right-hand side of Figure 9), a clear difference of 10 to 15 hPa is observed between the DT and TT cases in the equatorial region, almost independent of season. The maximum differences are usually observed in the extratropics and range from 25 to 30 hPa. The exception is the case of the NH during JJA, when a difference of 35 hPa is detected. For the temperature (Figure 10) clear differences are observed only in the equatorial region, where the temperature of LRT2 is about 5°C greater for DTs than for TTs. This difference is observed for all four seasons. In the extratropics, the temperature for TTs is very slightly greater than for DTs. For the NH polar cap the difference is small during MAM/JJA and around 3°C in SON/DJF. For the SH polar cap, the difference is appreciable only in MAM, when LRT2 is 5°C greater for TTs than for DTs.

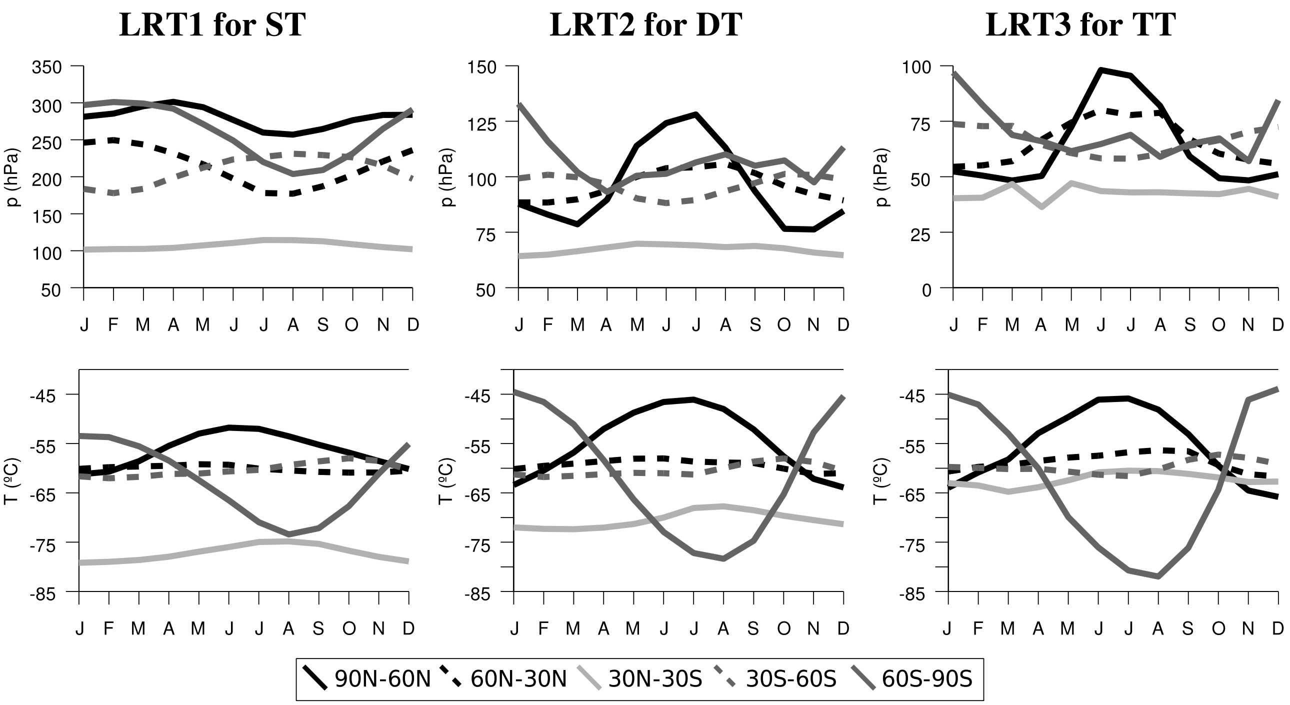

Figure 8. Intra-annual distribution of (top) pressure and (bottom) temperature for LRT1 in the case of ST, LRT2 in the case of DT, and LRT3 in the case of TT for the tropics, extratropics, and poles.

[34] The most important conclusion that can be drawn from Figures 9 and 10 is that LRT1 and LRT2 respectively are lower (higher pressure) for a MT event than for STs and for TTs than for DTs, respectively. A similar result has been reported by *Bischoff et al.* [2007]. According to the schematic tropopause model of *Shepherd* [2002], the behavior of LRT2 in the tropical regions suggests its occurrence in the lower stratosphere, with higher pressure corresponding to lower temperature. For the case of LRT1, in the extratropical regions, the increase of temperature with increased pressure suggests tropospheric characteristics.

[35] Figure 11 shows the intra-annual cycle of the difference between the last and the first lapse rate tropopause for MT events, for pressure, geopotential height, and temperature. The results were obtained by subtracting the values of the variables for LRT2 and LRT3 from those of LRT1 for the case of DTs and TTs, respectively. We call the resulting values for pressure ΔP_{12} and ΔP_{13} and use a similar convention for geopotential height and temperature. As in Figure 8, to achieve greater spatial resolution the study was performed by splitting the stations into five different regions (poles, extratropics, and equatorial region).

[36] ΔP_{12} and ΔP_{13} show similar behavior throughout the year. An annual cycle of vertical separation for the poles and extratropics is apparent. For the equatorial region, the differences can be considered to be constant, although the same undulate shape is observed with values ranging between 60 hPa and 65 hPa for ΔP_{12} and 90 hPa and 110 hPa for ΔP_{13}. It is noticeable that the poles show similar behavior in both hemispheres, while for the extratropics the behavior is opposite. The maximum amplitude of the annual cycle is present over the polar caps, with amplitudes of around 70 hPa for ΔP_{12} and ΔP_{13} in the NH and amplitudes of 100 hPa in the SH. The highest values of vertical separation are always found for the NH polar cap with maximum values of 229 hPa for ΔP_{12} and 267 hPa for ΔP_{13}, corresponding to vertical separations of 10.6 km and 13.4 km, respectively, what is a high separation compared with the mean height of the LRT1 itself.

[37] As far as temperature is concerned, the maximum amplitude of the seasonal cycle is found at the SH polar cap, with maximum values for ΔT_{12} of around 7.5°C during the hemispheric winter and about −11°C in November. For ΔT_{13}, it reaches 12°C in June and around −15°C in November. The NH polar cap shows the opposite effect and exhibits small variations throughout the year. A small intra-annual variability in the extratropics may be observed, with differences in ΔT not larger than 5.5°C. According to the sign of the temperature differences, during the whole year for the equatorial region, LRT1 is warmer than LRT2 and LRT3 throughout the year for the equatorial region, while for extratropics, LRT1 is cooler than both of them. In the poles, LRT1 is warmer than LRT2 during the hemispheric winter, while for summer the opposite is true. This difference in temperature is important because it is a signal of a more tropospheric or stratospheric behavior of LRT2 and LRT3 in the tropopause transition layer. That is, where LRT2 is cooler than LRT1, its behavior is more likely to be close to that of the troposphere while it is more probable to correspond to a tropospheric behavior; however where it is warmer its behavior is more likely to be close to that of the stratosphere than of the troposphere.

[38] These results disagree with those previously obtained by *Schmidt et al.* [2006] using GPS radio occultations. They found that the maximum pressure difference between the first tropopause and the last tropopause (in the limits of 500–70 hPa) corresponds to the extratropics, with

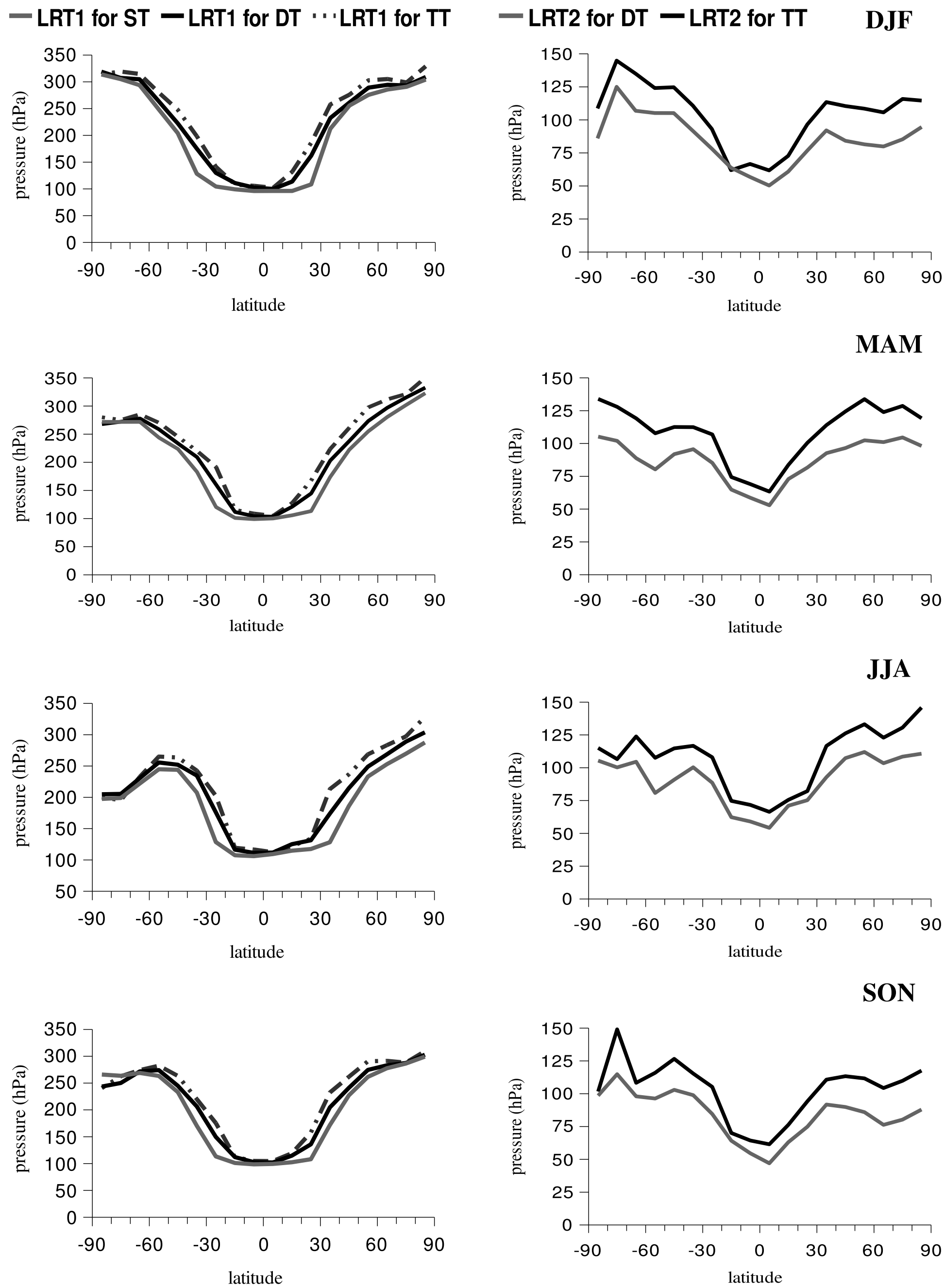

Figure 9. (left) Seasonal meridional distribution of pressure for LRT1, distinguishing between ST, DT and TT. (right) Seasonal meridional distribution of pressure for LRT2, distinguishing between DT and TT.

typical differences in pressure of 85 hPa. For this region, we obtained typical values for the difference in pressure ranging from 105 hPa to 175 hPa for ΔP_{12}, and greater values for ΔP_{13}. However, for temperature, we obtained similar maximum difference values of 7°C for ΔT_{12} (but they are not geographically consistent). Although we obtained these values for the poles, *Schmidt et al.* [2006] found these values for the extratropics, where we obtained values ranging from 2.5°C to 5°C for both ΔT_{12} and ΔT_{13}. However, the values of ΔP_{12} and ΔT_{12} obtained for the SH extratropics agree with the local values obtained previously for this zone by *Bischoff et al.* [2007], mainly with their results for extratropical high latitudes.

[39] Figure 12 shows the standard deviation plots corresponding to pressure and temperature in Figure 11. Typical values for ΔP_{12} are 35 hPa for the SH polar regions, 20 hPa for the NH polar regions, and 10 hPa for the tropics and extratropics. For ΔP_{13} the values oscillate around 50 hPa for the SH polar regions, and 25 hPa for the NH polar regions, tropics, and SH extratropics, while it is about 15 hPa for the NH extratropics. In the case of temperature, without mentioning values, two observed features are remarkable: the high values corresponding to the tropics and the SH polar regions during the hemispheric summer. This summer maximum must be

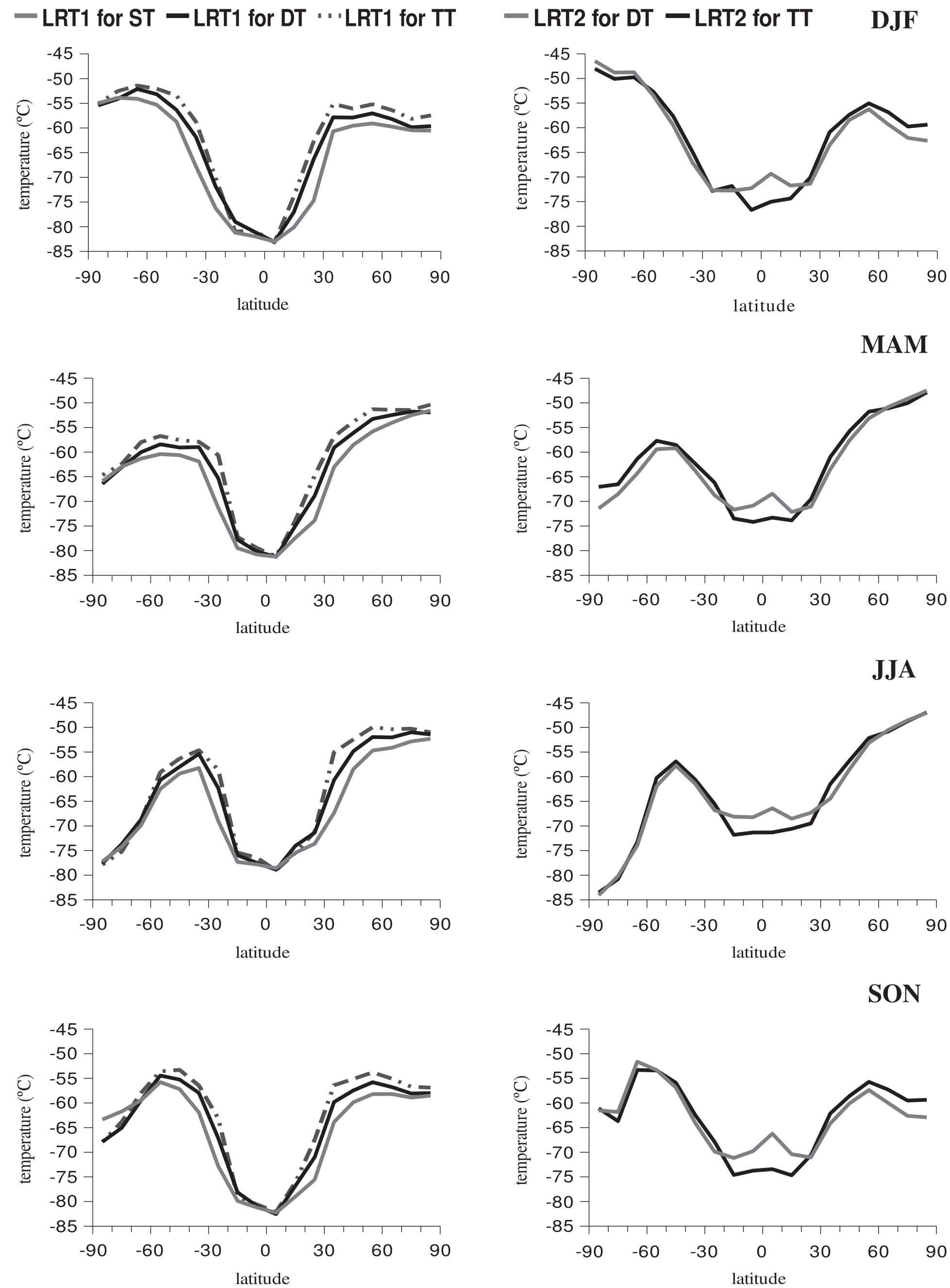

Figure 10. Similar to Figure 9 but for temperature.

taken with caution, given the small number of MT events in the data set for the SH polar region in this season.

4. Discussion

[40] We have presented climatological features of global multiple tropopauses from a comprehensive set of radiosonde data that covered a period of 40 years. We analyzed statistics for the occurrence of climatological features of the pressure and temperature, seasonal variations and vertical separation between first and last lapse rate tropopauses.

[41] The analysis shows a well-defined latitudinal band of maximum occurrence of MT events for the NH and three areas of maximum occurrence for the SH. In the case of the NH, these zones are clearly coincident with identified zones of maximum cyclogenesis. The bigger distribution of the stations over land areas and the possible influence on the spatial distributions derived from this kind of data must be taken into account. However, in some cases these maxima are poleward compared to previous results from the reanalysis of the global distribution of tropopause foldings obtained by *Sprenger et al.* [2003], which is a very probable cause of MT event detection when using radiosonde data. Good agreement with the results of *Randel et al.* [2007] was obtained. The bigger number of stations and soundings that we used, and therefore the greater area that was covered, enabled us to identify MT events for the whole year, which is a novel result compared with previous analyses.

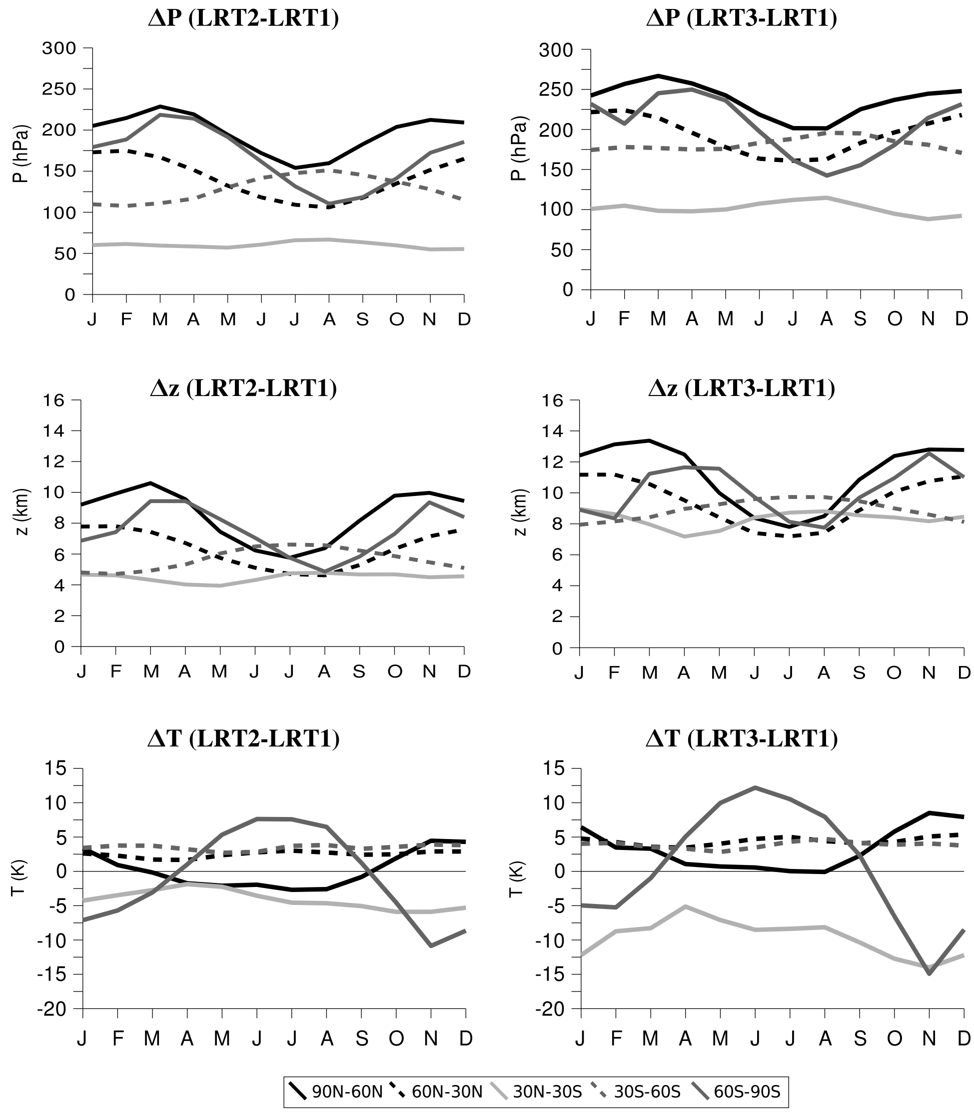

Figure 11. Intra-annual variation of pressure, height, and temperature differences between (left) LRT1 and LRT2 for DT and (right) LRT1 and LRT3 for TT. Results are shown split by latitude bands.

[42] The distribution of MT events coincides with the subtropical jet stream and the occurrence of cutoff lows, which is consistent with the findings of *Palmen and Newton* [1971] and *Bischoff et al.* [2007]. Moreover, the distribution of MT events shows reasonable agreement with the global pressure fields of LRT1 obtained by *Hoinka* [1998], which relate to the convergence of isobars in the observed zones of maximum occurrence during winter and the subsequent increase of the upper-level jet stream in summer as soon as the jet stream over Asia weakens [*Peixoto and Oort*, 1992]. However, it seems clear that further research is needed to investigate the interaction between the jet stream displacements and MT events and the correspondence with global occurrences of cutoff lows.

[43] The climatological features of pressure and temperature point to the complexity of these phenomena. LRT1 behavior is as expected, and it is as shown in a number of previous studies. LRT2 and LRT3, for DTs and TTs respectively, show a behavior that is clearly linked more closely with the lower stratosphere than the upper troposphere. This behavior makes necessary additional research about the true meaning of the lapse-rate tropopause definition and its role within the idea of a tropopause transition layer. The poles, in particular, show a great seasonal sensitivity. It must be taken into account that the vertical temperature variations over these regions are not as well marked as in the tropics or extratropics, which, in some cases, make it difficult to identify a clear tropopause using a lapse rate definition.

[44] The lowering of LRT1 in the case of MT events that had been found previously in local studies [*Bischoff et al.*, 2007] was confirmed for the whole globe, and was shown to be independent of the season.

[45] In order to come to a full understanding of the phenomena under study, it is important to determine the source of the strong seasonal dependence of the observed vertical separation between LRT1 and the last tropopause. Further research is required to determine whether LRT1 is the material layer separating the troposphere and the stratosphere or whether the seasonal dependence corresponds to

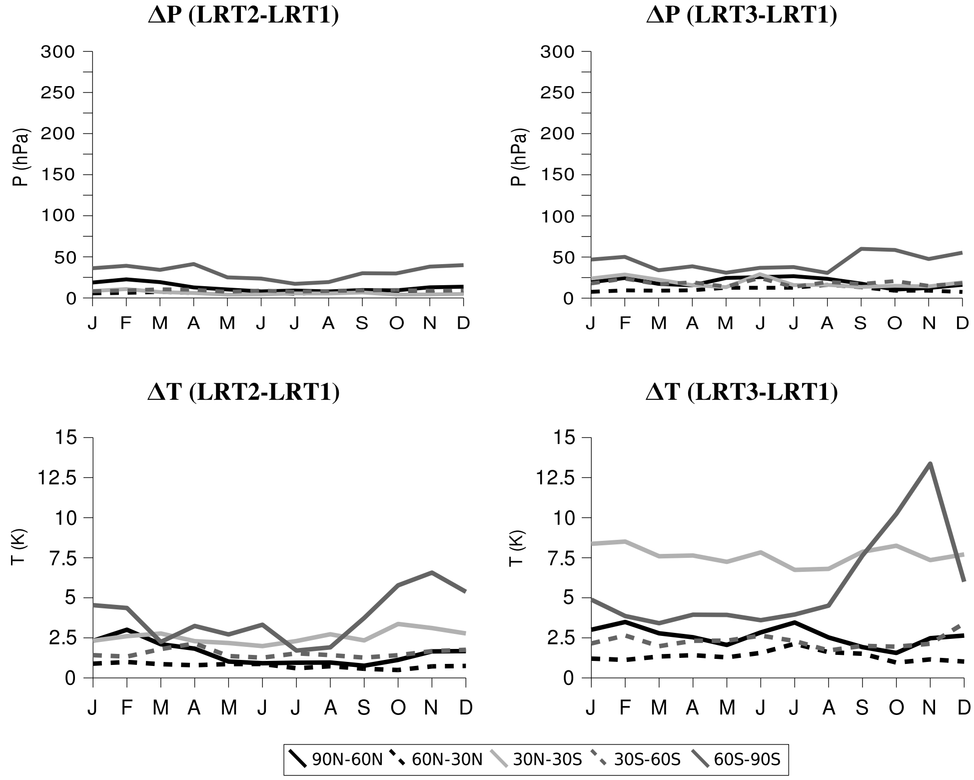

Figure 12. Standard deviation plots corresponding to Figure 11.

LRT2 and LRT3 in the case of MT events. It is also important to characterize the stability of the air masses between LRT1 and LRT2/LRT3 during MT events. It is necessary to perform analyses in addition to those previously performed by *Birner* [2006] using, for example, the buoyancy frequency. This topic has recently been addressed by *Bell and Geller* [2008].

[46] The combined intra-annual variation of the frequency of occurrence, pressures, and temperatures of MT events show notable differences for tropical and extratropical MT events. While the cited features of tropical MT events do not show seasonal cycles, there are strong seasonal cycles for the same variables in extratropical MT events. On the other hand, according the schematic tropopause model of *Shepherd* [2002], the behavior of LRT2 in the tropical regions suggests that it occurs in the lower stratosphere, whereas the behavior of LRT1, in the case of MT events in the extratropical regions, suggests that it occurs in the troposphere.

[47] This climatological view of MT events sheds some light on several of the key issues recently raised by *Gettelman et al.* [2007]. These are (1) finding a LRT3 that, in some cases, behaves in a manner more similar to the lower stratosphere and in others more similar to the known first tropopause (LRT1), (2) the predominant occurrence of MT events in extratropical regions, and (3) the difficulty of finding an interpretation of the behavior over the poles that goes beyond considerations about the instrumentation and the vertical profile. All these factors demonstrate the need for a more precise definition of the tropopause, and more detailed studies of its nature and its role in atmospheric processes. Finally, the spatial and temporal coverage of this study, with the fields and statistics obtained, can, perhaps, serve as the baseline for further work on the topic.

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