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# Global statistics of multiple tropopauses from the IGRA database

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[1] We present statistics for the occurrence of multiple tropopauses for the entire globe, derived from the meteorological sounding data contained in the Integrated Global Radiosonde Archive (IGRA). The IGRA is the most comprehensive and largest radiosonde data set compiled to date, with more than 1500 stations and data starting from 1938. Statistics were derived from (a) the IGRA tropopause reports (reported tropopauses) and (b) tropopauses calculated from the sounding profiles reported in the IGRA (calculated tropopauses). This work constitutes a necessary precursor to conducting better research on the phenomena of multiple tropopauses and promotes understanding of the global structure of these events. Among other things, we calculated global counts and the latitudinal distribution of percentages of tropopauses with respect to the number of soundings, percentages of second and third tropopauses with respect to the first tropopause, and mean values of pressure and temperature of multiple tropopauses. **Citation:** Añel, J.A., J. C. Antuña, L. de la Torre, R. Nieto, and L. Gimeno (2007), Global statistics of multiple tropopauses from the IGRA database, *Geophys. Res. Lett.*, *34*, L06709, doi:10.1029/2006GL029224.

## 1. Introduction

[2] The tropopause has been the subject of increasing scientific interest, due to its being the transition layer between the troposphere and the stratosphere. Its complex structure is determined by its location on top of the mainly convectively driven troposphere and at the bottom of the predominately radiatively controlled stratosphere. Among the subjects of interest is its role in the stratosphere-troposphere exchange of water, mass and chemical compounds [*Holton et al.*, 1995]. Another source of interest concerns the possible role of the temporal variation of its height (or pressure) as a fingerprint for cyclone-anticyclone asymmetry [*Wirth*, 2001] and for natural and anthropogenic climate change [*Santer et al.*, 2003; *Sausen and Santer*, 2003; *Añel et al.*, 2006]. Although the tropopause is generally conceived of as a layer, for practical purposes it is often considered as a surface. In that context, the study of the occurrence of multiple tropopauses is central to the understanding of the structure and features of such a layer. *Schmauss* [1909] was the first to note the occurrence of multiple tropopauses. Later, *Bjerknes and Palmen* [1937] investigated this kind of structure, which they named "the sub-stratosphere". To the authors' knowledge, only three works have addressed multiple tropopauses on a global scale: the global climatology of multiple tropopauses derived from Global Positioning System (GPS) radio occultations developed recently by *Schmidt et al.* [2006], and two earlier works conducted in the former Soviet Union using radiosonde data [*Makhover*, 1979, 1983]. Other studies have addressed multiple tropopauses from radiosonde locally [*Harsson*, 1971; *Varotsos et al.*, 2004; J. C. Antuña et al., Behaviour of the tropopause at the Camagüey meteorological site. part I: Aerological variables (in Spanish), unpublished manuscript, 1992, available from the Camagüey Meteorological Centre Library, Camagüey, Cuba]. There are no studies of multiple tropopauses from reanalysis data due to the low vertical resolution and attendant biases, so radiosondes continue to be the most important data sources for determining tropopause parameters with a climatic perspective [*Randel et al.*, 2000].

[3] We here present statistics of multiple tropopauses a) derived directly from the Integrated Global Radiosonde Archive (IGRA) tropopause reports and b) calculated by us from the sounding profiles reported by the IGRA. In Section 2, we describe the data set and the method of analysis. In Section 3, we describe the different statistics calculated. In Section 4, we summarize and discuss the results.

## 2. Data Set and Methods

[4] In the first part of the study reported herein, we used the multiple tropopause reports from meteorological sounding messages contained in the IGRA data set from the beginning of the IGRA database (1938) to December 2004. The IGRA is the most recently assembled, most comprehensive, and largest radiosonde data set, with more than 1500 stations. It combines different data sources and applies quality control algorithms to remove gross errors [*Durre et al.*, 2006]. The unrestricted access to the data, as well as its continuous updating, makes this data set a valuable tool for operational and research purposes.

[5] The first remarkable feature of the tropopause reports in the IGRA is that while data collection began in 1938, the first tropopause reports occur in 1969 and their number is not significant before 1971. The criterion used to compute the tropopauses reported in the IGRA and subsequent multiple tropopauses is the usual thermal definition, as stated by the World Meteorological Organization [*World Meteorological Organization*, 1957, pp. 136–137]:

[6] "(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.

[7] (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

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**Table 1a.** Percentage of Reports of Multiple Tropopauses With Respect to the Total Number of Soundings at Each Observation Time[a]

| | IGRA (Reported), % | 188-Station Subset (Calculated), % |
|---|---|---|
| 1st Tropopause | 41.09 | 70.74 |
| 2nd Tropopause | 6.08 | 11.63 |
| 3rd Tropopause | 0.53 | 1.94 |

[a]Results are shown for the reports in the complete IGRA database and for the calculated data from the used global subset.

**Table 1b.** Percentage of Soundings Reaching 10, 15 and 20 km at Each Observation Time[a]

| | IGRA (Reported), % | 188-Station Subset (Calculated), % |
|---|---|---|
| 10 km | 70.88 | 89.65 |
| 15 km | 63.82 | 80.64 |
| 20 km | 42.75 | 59.4 |

[a]Results are shown for the reports in the complete IGRA database and for the calculated data from the used global subset.

same criterion as under (a). This tropopause may be either within or above the 1km layer."

[8] A typical temperature profile for a sounding with a triple tropopause case is shown in Figure S1 in the supplementary material.[1]

[9] Despite the quality control exercised when generating the IGRA data set, there is no guarantee that the tropopause reports are homogenous, in either space (at different stations) or time (during the whole period of data available for each station). This potential lack of homogeneity is due to problems with the original sounding reports themselves and should not be attributed to the design and building of the IGRA data set. Such problems are listed in the supplementary material. In spite of these problems, the IGRA is still suitable for climatological studies and have been recently used for other tropopause studies [*Seidel and Randel*, 2006]. Previous studies have pointed out that the lack of data in the IGRA with respect to the original sounding reports in stations does not produce statistically significant changes in temperature or pressure mean values at the multiple tropopause levels [*Antuña et al.*, 2006]. Hence, we used only pressure and temperature information from the tropopause levels.

[10] Moreover, we calculated the tropopause from the original sounding profiles reported using criteria specified by the WMO. The tropopauses calculated by us were derived from a global subset of 188 radiosounding stations, instead of all stations included in the IGRA. The used subset is based on that developed previously by *Wallis* [1998]. This subset guarantees homogeneous global spatial coverage, so calculated tropopause statistics are comparable with those from the IGRA reports. Detailed information about the used subset may be found in the supplementary material (Table S1 and Figure S2). Two key methodological features for the calculated tropopauses are (a) the possibility of calculating geopotential heights at those levels at which they are missing from the IGRA reports if pressure data are available for those levels, and (b) the possibility of interpolating parameters for a level if these are missing from the IGRA reports.

## 3. Results

### 3.1. Global Frequency of Tropopauses

[11] The IGRA contains almost 5,5 million tropopause reports for the studied period for the entire globe, of which around 75% are from stations located in the Northern Hemisphere. Tables 1a and 1b show the percentage of reports of multiple tropopauses globally out of the total number of tropopause reports, both from original IGRA reports and calculated by us using the sounding profiles from the IGRA. The percentage was calculated by reference to the total number of soundings in the data set. As was expected, the percentage of tropopauses calculated by us is greater than that reported in the IGRA, being near to double for first and second tropopauses and almost four times greater for triple tropopauses. The percentage of reports of the second and third tropopauses with respect to the number of reported and calculated first tropopauses is displayed in Table 1c. The higher percentages represent the case of tropopauses calculated by us; however, for second tropopauses the value is very similar for both reports and calculations. There are several cases with a reported fourth tropopause (and at the extreme, there are (obviously erroneous) cases with even a ninth tropopause), but taking into account their scarcity, we decided not to include them in this paper.

### 3.2. Frequency of Tropopauses by Latitude

[12] A latitudinal study has special importance for the tropopause, because one of its main features is the latitudinal variation of its height, which is higher over the equatorial zone and decreases poleward. The opposite is true for pressure: pressure is greater over the poles and decreases towards the equatorial zone. Moreover, the spatial and temporal distribution of soundings, and the maximum height reached, is different for each different latitude band. This information is very valuable for future research, because a good knowledge of the mean measurement conditions is very important for precise interpretation of the obtained results. Figure 1 shows the latitudinal distribution of stations and number of soundings in the IGRA by 10° latitude bands. As expected, the minimum of both occurs in polar zones, with a well-defined maximum at Northern Hemisphere midlatitudes (between 30°N and 40°N for the entire list of IGRA stations and between 50°N and 60°N for soundings and stations corresponding to the subset of 188 stations). The reason for this discrepancy is the larger number of stations in this region of the globe that perform four soundings daily instead of two,

**Table 1c.** Percentage of Reports of Second and Third Tropopauses With Respect to the Total Number of First Tropopauses[a]

| | IGRA (Reported), % | 188-Station Subset (Calculated), % |
|---|---|---|
| 2nd Tropopause | 14.79 | 16.44 |
| 3rd Tropopause | 1.29 | 2.75 |

[a]Results are shown for the reports in the complete IGRA database and for the calculated data from the used global subset.

[1]Auxiliary material data sets are available at ftp://ftp.agu.org/apend/gl/2006gl029224. Other auxiliary material files are in the HTML.

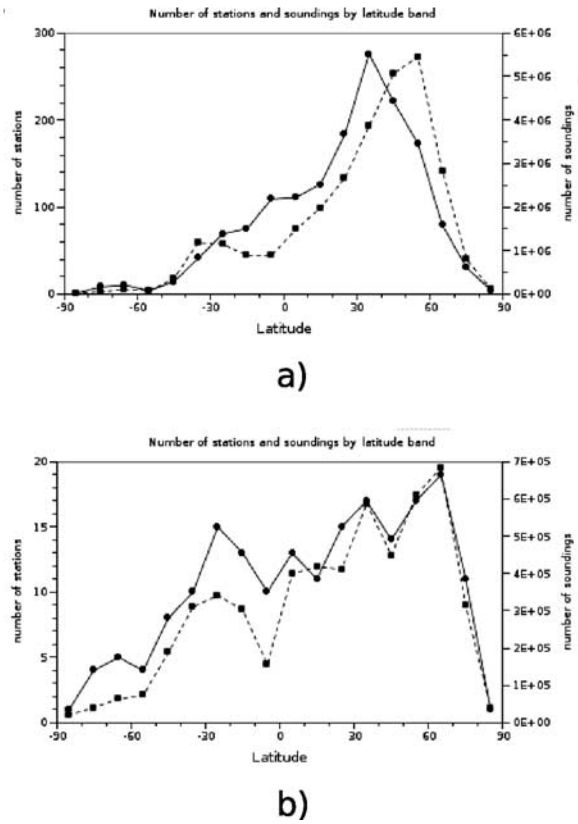


**Figure 1.** (a) Latitudinal distribution of stations (solid line) and number of soundings (dashed line) in the whole IGRA data set and (b) the same, but showing data for the subset used (see Table S1 and Figure S2 in the supplementary material) for tropopauses calculated by us.

which is the most common number (00Z and 12Z). The number of cases of first, second and third tropopauses reported in the IGRA is slanted to the extratropics of the Northern Hemisphere. Obviously, this is a logical consequence of there being more stations in this region with a larger temporal sounding series, which soundings were then included in the IGRA. For the case of calculated tropopauses, the influence of the spatial distribution of stations is not so obvious because of the nature of the subset of stations used, which ensures spatial homogeneity.

[13] Figure 2 shows the percentage of soundings that reached an altitude of 20 km, the percentage of first tropopauses with respect to the total number of soundings, and the percentage of double and triple tropopauses with respect to the number of first tropopauses, at each 10° latitude band from 90°S to 90°N. The results are shown for the reports included in the IGRA and for the calculated tropopauses. A lower percentage of the number of soundings reaches 20 km for the tropical zone in the IGRA (about 20%) than for the extratropical zones (more than 40%). In general terms, the percentage of calculated tropopauses is greater than the percentage of reported ones. First, double and triple tropopauses show a similar shape for the latitudinal percentage of reported and calculated tropopauses with maximum values at high latitudes of about 80%, 30% and 2% for the reported ones, and 95%, 30% and 6.5% for the calculated ones, respectively. The explanation for such behavior could be associated with the fact that the tropopause height increases from the poles to the tropics and at the same time the number of soundings reaching higher altitudes decreases from the poles to the equator, thereby reducing the likelihood of the radiosonde reaching the tropopause. The maximum percentage of reports of triple tropopauses in the NH is reached at around 30°N, being coincident with the double tropopauses' maximum. In the SH, there are two maxima of similar magnitude at 40°S and 70°S for the reported tropopauses, while for the calculated ones there is only a well-marked maximum at 60°S. It is worthy of note that the maxima for double and triple tropopauses appear in the zone of the jet streams for both hemispheres. This observed behavior could be linked with there being more tropopause foldings in these regions, which is coincident with the results previously obtained by *Sprenger et al.* [2003]. Differences between the percentages of first tropopauses reported and calculated range from 40% to 5%. However, the observed latitudinal profile for the case of double tropopauses is very close for reported and calculated ones, especially for the Southern hemisphere. The largest differences occur for triple tropopauses, the percentage of calculated triple tropopauses being more than three times than that of reported triple tropopauses. If we consider only soundings reaching altitudes higher than 20 km (see Figure S3 in the supplementary material), the percentage of both reported and calculated multiple tropopauses increases, peaking at almost 100%, 35% and 8% for the first, second and third calculated tropopauses, respectively, and being slightly lower for reported tropopauses.

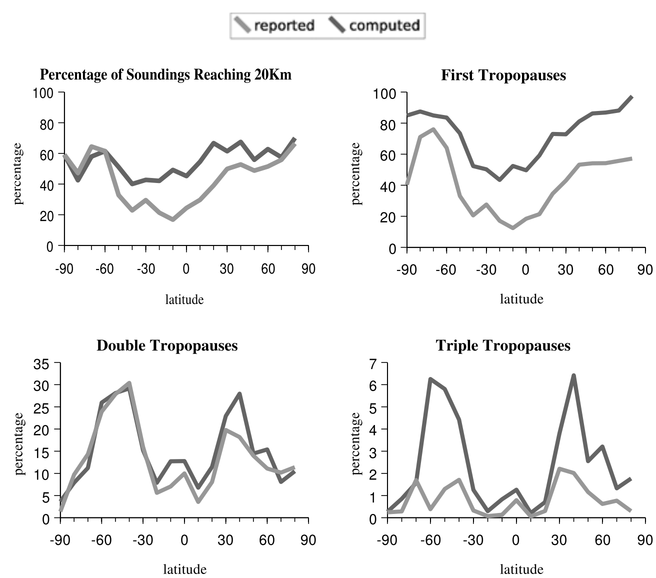


**Figure 2.** Latitudinal distribution of (top left) percentage of soundings reaching 20 km, (top right) percentage of first tropopauses with respect to the total number of soundings, (bottom left) percentage of double tropopauses with respect to the number of first tropopauses, and (bottom right) percentage of triple tropopauses with respect to the number of first tropopauses. Results are shown for both full IGRA reports (reported) and the 188-station subset (calculated).

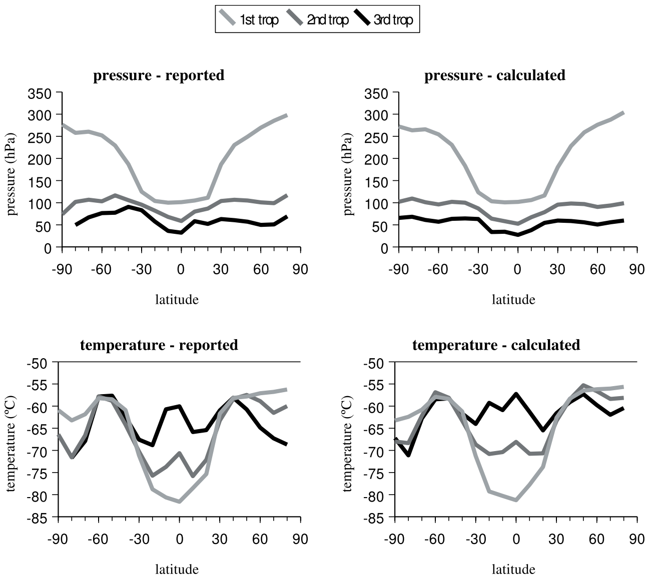


**Figure 3.** Latitudinal distribution of the mean values of pressure and temperature for the multiple tropopauses (reported and calculated). The reported cases with values greater than 500 mb for the first tropopause have been removed.

### 3.3. Mean Values of Pressure and Temperature

[14] Figure 3 shows zonal mean values of pressure and temperature for the first, second and third tropopauses. Taking into account only soundings reaching 20 km, the obtained results are very similar (see Figure S4 in the supplementary material). In several cases, there were anomalous pressure values of reported tropopauses, with pressure values being too high (and in some cases close to 1000 hPa) for the first tropopause. Obviously, these reported tropopauses are errors contained in the IGRA. Some of them could correspond to thermal inversions in the low or medium troposphere erroneously flagged as tropopauses, which passed the IGRA quality and homogenization controls. In order to avoid their erroneous influence on the mean pressure in Figure 3, all cases with first tropopauses presenting pressure values greater than 500 hPa were removed. The influence of these erroneous tropopauses could be higher for the third tropopause, because of the smaller number of existing cases. For instance, the number of reported third tropopauses with values in the range from 700 hPa to 800 hPa represents about 30% of the total number of third tropopauses reported for the latitude band from 15°N to 20°N. The meridional structure of pressure for the first tropopause is as expected, with maximum mean values rounding 270 hPa over the poles and decreasing to the equator with values about 100 hPa for the tropical regions (30°N–30°S). For the second and third tropopauses, the pressure differences between the poles and equator are not so evident, with a difference of 40 or 50 hPa. The mean values of pressure are very similar for the case of reported and calculated tropopauses, except for the double and triple tropopauses in the latitude band of 40°S–50°S, where the mean pressure is slightly higher in the case of reported tropopauses than for the calculated ones. The meridional structure of the first tropopause temperature is also as expected, being higher in the tropics than in the extratropics. The values of temperature agree very closely with previous studies, such as *Schmidt et al.* [2006], with values rounding −60°C and −55°C over the South and North Poles respectively and about −80°C for the equatorial region. The latitudinal distribution of temperature for the second and third tropopauses has the expected profile in extratropical regions, with an unexpected warming in the equatorial zone (respectively 10 and 15 degrees for the reported and calculated tropopause in comparison with the results obtained by *Schmidt et al.* [2006]). This result suggests that the first tropopause in the tropics is the "so-called" cold point tropopause (the point where the vertical gradient of temperature becomes positive), and the second and the third tropopauses calculated from WMO definitions are placed in regions with stratospheric regimes [*Gettelman and Forster*, 2002]. For the second tropopause, the values range from −55°C in midlatitudes on both hemispheres for the case of the calculated tropopause (about 2 or 3 degrees colder for the case of reported tropopause) to −70°C near to the equator for the calculated tropopause (about −75°C for the reported tropopause). The usual difference in temperature at polar regions between the North and South Hemispheres is also observed. For the third tropopause, temperature minima are found over the poles, with values of −70°C for the Southern and Northern Hemispheres. Maximum values of temperature are located on the midlatitudes of both hemispheres and also on the equator, with values around −57°C. If we recalculate the mean pressure and temperature latitudinal profiles but consider only cases with three tropopauses reported or calculated, the results are very similar (see Figure S5 in the supplementary material). The obtained results present a comprehensive view of the mean global climatological features of the multiple tropopause events, yielding a deeper understanding of the phenomena as their mean thermodynamic conditions or their most frequent area of occurrence near the jet systems. The results also promote a better understanding of the tropopause and the structure of the lower stratosphere.

## 4. Summary and Concluding Remarks

[15] Statistics of the multiple tropopauses were calculated from IGRA sounding reports, including global counts and latitudinal distribution of percentages of reports of tropopauses with respect to the number of soundings, percentage of reports of second and third tropopauses with respect to reports of the first tropopause, and mean values of pressure and temperature of multiple tropopauses.

[16] The number of double and triple tropopauses is at a maximum near to the subtropical jet streams for both Hemispheres and near to the polar jet stream region for the Southern Hemisphere. This fact could be explained either by a possible relationship between the occurrence of double tropopauses and relatively large vertical advective movements [*Harsson*, 1971] or by the existence of tropopause foldings in jet-stream regions [*Elbern et al.*, 1998]. This higher occurrence of multiple tropopauses close to jet stream systems was also noted by *Schmidt et al.* [2006]. No important differences were observed when we considered only soundings reaching 20 km.

[17] The meridional structure of the mean pressure for the different tropopauses follows the known pattern of lower pressure over the equatorial zone increasing poleward. Here, a noticeable difference from other previous studies was found. *Schmidt et al.* [2006] obtained the maximum difference between the pressure of the first tropopause and the last tropopause (their method always supposes that the last tropopause reaches a pressure greater than 70 hPa) for 30°–50° on both hemispheres with values of 85 hPa. By contrast, the maximum pressure difference between the first and the third tropopause in our study occurs in the polar regions with values rounding 200 hPa. For the 30°– 50° band in the NH we obtain differences of 165 hPa and 115 hPa with the third and second tropopause respectively. For the SH these differences round 205 hPa and 150 hPa. The reason for this discrepancy with *Schmidt et al.* [2006] is unknown. However it must be highlighted that the meridional pressure values for the computed tropopause (using the subset of stations) are always lower than the 70 hPa limit used by them. In this way the last tropopause computed by *Schmidt et al.* [2006] is closer to our second tropopause than the third. The latitudinal distribution of the temperature of the first tropopause was as expected and in accordance with previous studies, so the mean values obtained (−81°C for the equatorial zone) are very similar to those found previously by *Hoinka* [1999] using reanalysis data and *Schmidt et al.* [2004] using GPS radio occultation techniques. The difference of about 25°C between the equatorial zone and the poles observed in our study is also coherent with results found in these two previous studies. The meridional structure of temperature for the second and third tropopauses over the equator differs from the results of previous studies. According to our results, temperature increases over the equator instead of having a temperature similar to the first tropopause, as expected and previously found by *Schmidt et al.* [2006]. For the cases with only three tropopauses, this increase is removed for the second tropopause but being yet warmer than the first tropopause, obviously remaining for the third tropopause because the data are not modified respect the previous analysis. This fact suggests the possibility that the third tropopause observed is related more to stratospheric behavior than tropospheric.

[18] Moreover, it is remarkable the occurrence of multiple tropopause events for all the latitude bands along the whole year. Previous studies [*Seidel and Randel*, 2006] have reported that in several stations the second tropopause was not found in some of the seasons. In conclusion, sounding reports in the IGRA seem, in general, to constitute a suitable database for the study of the tropopause and multiple tropopauses. The obtained results seems reasonable and concordant with other previous using other data sources. Moreover this fact has been previously pointed out by *Antuña et al.* [2006]. However, it would be much more reliable to recalculate tropopause parameters directly from a set of IGRA soundings after applying procedures that ensure spatial and temporal homogeneity. These procedures are usually based on the identification of artificial discontinuities using computational methods and the visual examination of graphics and metadata [*Lanzante et al.*, 2003]. This would be especially important for ensuring the reliability of the results and the objective of our subsequent work.

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