



Recent widening of the tropical belt: Evidence from tropopause observations

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[1] Radiosonde measurements and reanalysis data are used to examine long-term changes in tropopause behavior in the subtropics. Tropopause heights in the subtropics exhibit a bimodal distribution, with maxima in occurrence frequency above 15 km (characteristic of the tropical tropopause) and below 13 km (typical of the extratropical tropopause). Both the radiosonde and reanalysis data show that the frequency of occurrence of high tropopause days in the subtropics of both hemispheres has systematically increased during the past few decades, so that tropical characteristics occur more frequently in recent years. This behavior is consistent with a widening of the tropical belt, and the data indicate an expansion of about 5–8° latitude during 1979–2005.

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1. Introduction

[2] Climate model simulations for the late twentieth century show warming of the troposphere, cooling of the stratosphere, rising of the tropopause, and poleward movement of the midlatitude jet streams. Analyses of observations for the past few decades provide evidence for such trends [Trenberth *et al.*, 2007, and references therein]. One aspect that has received relatively little attention is possible latitudinal expansion of the tropical belt [Fu *et al.*, 2006], consistent with warming of the subtropical troposphere, rise of the subtropical tropopause, and poleward movement of the subtropical jets. This paper investigates changes in the width of the tropical belt as seen through observations of tropopause height, an indicator offering a clear distinction between tropical and midlatitude conditions.

[3] Our interest in a tropopause-based view of changes in the width of the tropics is motivated by several recent lines of research. Hudson *et al.* [2003] have shown that total column ozone in the Northern Hemisphere (NH) has relatively constant and distinct values in the tropics, midlatitudes, and polar regions if these zones are defined as meteorological regimes (rather than by fixed geographic latitudes) separated by the subtropical and polar fronts, with characteristic tropopause heights associated with each regime. Ozone trends in these regimes reveal changes in the area of each regime, with a $\sim 1^\circ$ latitude per decade northward movement of the NH subtropical front during 1979–2003 [Hudson *et al.*, 2006]. Similarly, the region of a sharp latitudinal gradient in tropopause height, found in the subtropics, has been shown to have moved poleward in both hemispheres in reanalysis and radiosonde data (T. Reichler,

personal communication, 2007). Fu *et al.* [2006] show evidence of tropical belt widening through analysis of tropospheric and stratospheric temperature observations from the microwave sounding unit for 1979 to 2005. The global pattern of trends, with maximum tropospheric warming and stratospheric cooling in the 15–45° latitude bands of both hemispheres, implies poleward shift of the latitude of maximum meridional tropospheric temperature gradient and associated poleward movement of the jets. Through analysis of outgoing long-wave radiation and mean meridional mass stream function data, (Y. Hu and Q. Fu, Observed poleward expansion of the Hadley circulation since 1979, submitted to *Atmospheric Chemistry and Physics*, 2007, hereinafter referred to as Hu and Fu, submitted manuscript, 2007) demonstrate that the tropical Hadley circulation expanded from 2 to 4.5° of latitude during 1979–2005.

[4] A similar, but smaller, signal also emerges in simulations of future climate change. Lu *et al.* [2007] show that 14 climate models project poleward expansion of the Hadley circulation of up to 1.5° latitude over the 21st century and that this expansion is correlated with increased extratropical tropopause height. Leroy *et al.* [2006] suggest that symmetric poleward migration of the midlatitude jets is an optimal climate change detection signal that will more quickly manifest itself than other climate change signals.

[5] This paper approaches the issue of tropical belt widening through analysis of tropopause observations. Radiosonde and reanalysis data show evidence that the tropopause has risen in the past 2–3 decades both in the tropics [Randel *et al.*, 2000; Seidel *et al.*, 2001; Zhou *et al.*, 2001] and globally [Hoinka, 1998; Santer *et al.*, 2003] in association with stratospheric cooling and, less strongly with, tropospheric warming [Seidel and Randel, 2006]. Here we are concerned with a distinct feature of the tropopause in the subtropics, where the tropopause is

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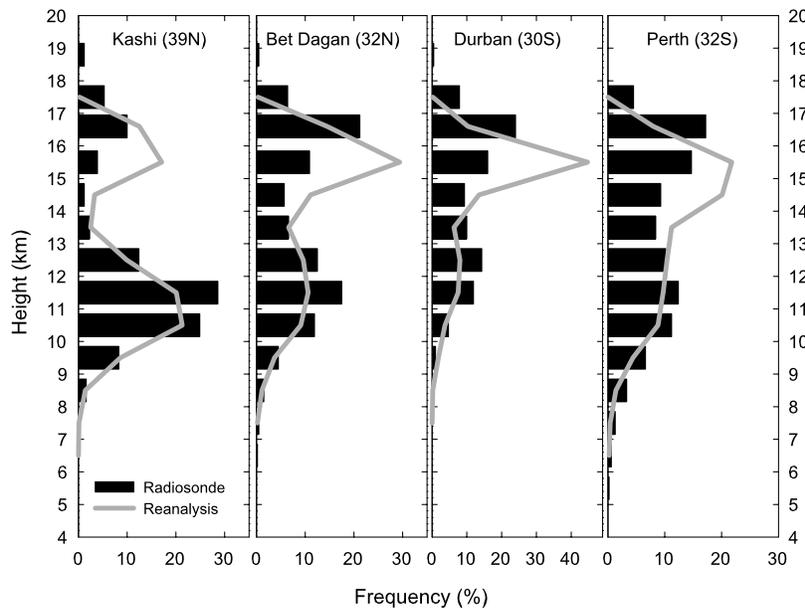


Figure 1. Bimodal probability densities of tropopause height at four subtropical radiosonde stations (black bars) and at corresponding grid points of the NCEP/NCAR reanalysis (grey lines), based on daily data for 1979–2005.

sometimes tropical and sometimes extratropical in character. Both radiosonde observations and the National Centers for Environmental Prediction (NCEP)/National Center for Atmospheric Research (NCAR) reanalysis data (described in section 2) reveal a clear distinction between the two regimes (section 3) and an increase in the frequency of tropical tropopause conditions in subtropical regions during recent decades, consistent with a widening of the tropical belt (section 4).

2. Radiosonde and Reanalysis Data

[6] We analyzed daily or twice daily radiosonde observations from a 100-station global network, described by Seidel and Randel [2006], for the period of 1960–2005. These data have relatively sparse spatial coverage but relatively long and complete time records. We also examine the spatially complete daily NCEP/NCAR and ERA40 reanalysis data [Kistler et al., 2001; Uppala et al., 2005]. However, we restrict our study of the reanalysis data to the period since 1979 because of inhomogeneities in the prior data [Randel et al., 2000]. For each sounding we determine the height of the lapse-rate tropopause, and compile annual statistics from the daily observations. For the NCEP/NCAR reanalysis we use the daily tropopause height provided, and for the ERA40 reanalysis we compute tropopause height in the same manner as for the radiosonde data. Because ERA40 ends in August 2002, we rely more heavily on the NCEP/NCAR reanalysis.

3. Climatological Features of Tropopause Heights

[7] For each radiosonde station and reanalysis grid box we computed the probability density function (pdf) of tropopause height by binning all the data for 1979 to 2005 in 1-km bins, from the surface to 20 km altitude.

Figures 1, 2, and 3 show that tropopause height exhibits a bimodal distribution consistently throughout the subtropics of both hemispheres. Figure 1 shows the pdfs from four subtropical radiosonde stations, two in each hemisphere, and corresponding pdfs from the NCEP/NCAR reanalysis. In each case the pdf is bimodal, with one mode above 15 km

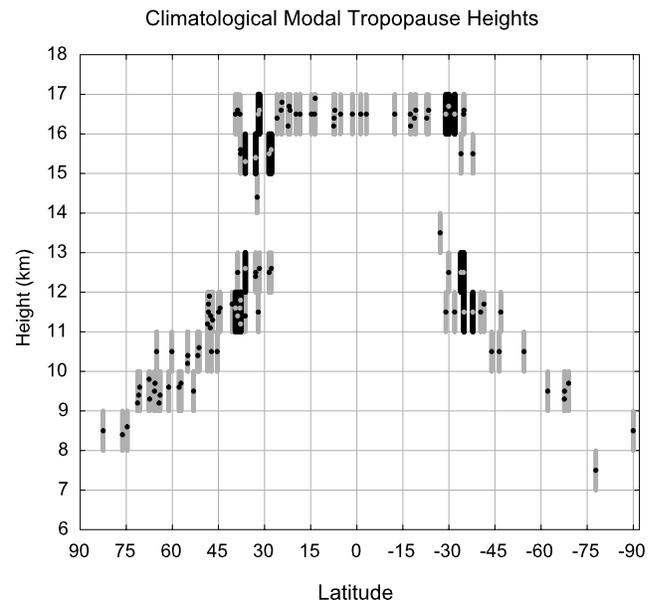


Figure 2. Modal values of tropopause height at each radiosonde station, based on 1 km height bins. Modal heights are shown as grey bars. For stations with bimodal distributions the primary mode is shown as a black bar. The number of small dots in each bar indicates the number of stations at that latitude.

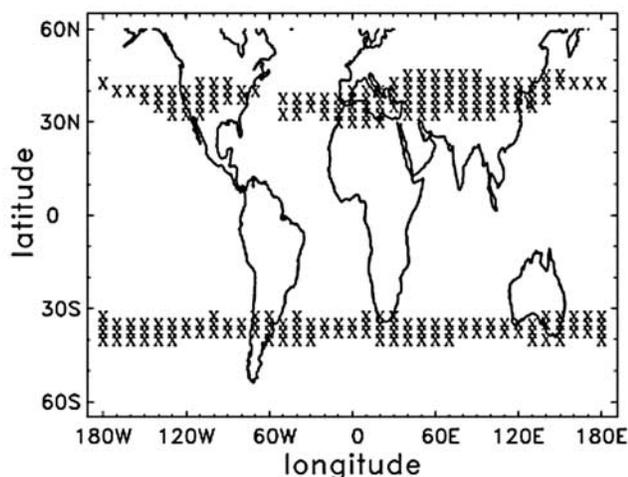


Figure 3. Locations (marked with a cross) of bimodal tropopause height probability distribution functions in NCEP/NCAR reanalysis data for 1979 to 2005, based on 1 km height bins.

(characteristic of the tropical tropopause) and another below 13 km (typical of extratropics). The upper mode is consistently in the 16–17-km bin in the radiosonde data and in the 15–16-km bin in the reanalysis. This difference is likely due to the poorer vertical resolution of the reanalysis and its reliance on satellite data, especially in the Southern Hemisphere (SH) [Birner *et al.*, 2006], where the reanalysis pdfs are less like those from radiosonde data than they are in the NH.

[8] This bimodal structure is only found in the subtropics. Figure 2 depicts the modes of the tropopause height pdfs for all 100 radiosonde stations as a function of station latitude. Modes were identified when the occurrence frequency for a given bin both exceeded 5% and exceeded the frequencies for both of the adjacent bins. Bimodal distributions were identified when two such modes existed.

[9] Radiosonde stations poleward of 40° latitude and equatorward of ~28° latitude exhibit unimodal pdfs. Modal heights are <13 km in the extratropics of both hemispheres and are uniformly in the 16–17 km bin within the tropical belt. The spatially complete reanalysis demonstrates that these features are very coherent. Figure 3 shows the locations of reanalysis grid boxes with bimodal tropopause height pdfs. They are in a 10–15° latitude band poleward of 30° latitude, spanning almost all longitudes in both hemispheres. In general, the upper mode is the primary mode (black bars in Figure 2) at the subtropical stations closer to the equator, and the lower mode is the primary mode at the subtropical locations closer to the poles.

[10] Thus in the subtropics the tropopause is sometimes at the height of the tropical tropopause and other times at a height typical of the extratropical tropopause. Most importantly for this study, there is a clear separation of about 3–5 km, between the modes. This feature is not simply a reflection of seasonal variability. High and low tropopauses are observed in all seasons at a given station, although on summer (winter) days the tropopause does tend to be high (low).

[11] Guided by these climatological pdfs, we associate tropopause heights >15 km with tropical conditions. On the basis of NCEP/NCAR reanalysis data, Figure 4 shows the climatological number of days per year with tropopause heights of >15 km. Poleward of 40° latitude tropopause height exceeds 15 km less than 10% of the time. Equatorward of 30° latitude tropopause height is higher than 15 km more than half the time, and within 20° of the equator it exceeds 15 km more than 85% of the time. The very zonal pattern of this climatological statistic, combined with the steep latitudinal gradient in the subtropics, makes it a simple and robust measure of the width of the tropical belt. The separation of the two climatological 300 d/a isolines yields an average width of the tropical belt of 43° latitude. That width is greater, 57 or 66°, based on the 200 or 100 d/a isolines, respectively.

4. Trends in Tropopause Height and Tropical Belt Width

[12] Figures 5 and 6 examine trends in tropopause height in the subtropical regions, specifically the frequency of occurrence (number of days per year) of tropical (>15 km) tropopause levels. Figure 5 shows trends in the frequency of high tropopauses at subtropical radiosonde stations for 1960 to 2005 (left) and for 1979 to 2005 (right). Our earlier study [Seidel and Randel, 2006] showed upward tropopause trends during the shorter period at these latitudes and globally but did not examine the earlier period because of data homogeneity issues. The categorical tropopause height metric examined here is much less susceptible to the effects of changes in instrumentation and observing practices than the actual tropopause height, so we have not restricted this analysis as severely. In Figure 5, trends were computed only if daily data were available for at least 80% of the days per year and at least 80% of the years for 1979 to 2005. For the longer period, 1960–2005, this restriction was relaxed to 66.6%, because no SH stations met the 80%

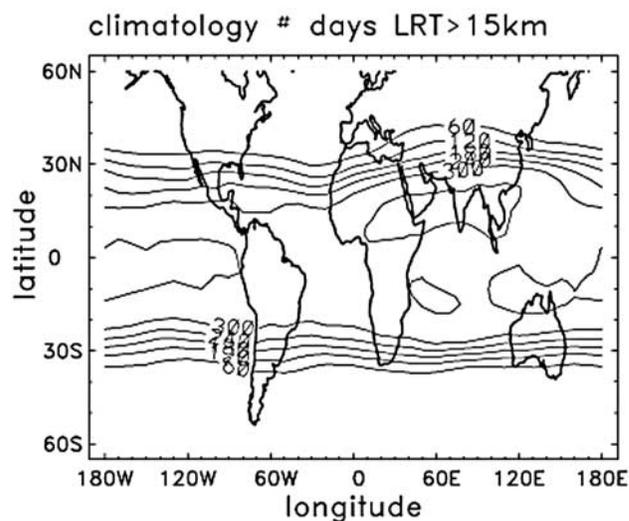


Figure 4. Climatological number of days per year with tropopause height >15 km, based on NCEP/NCAR reanalysis data.

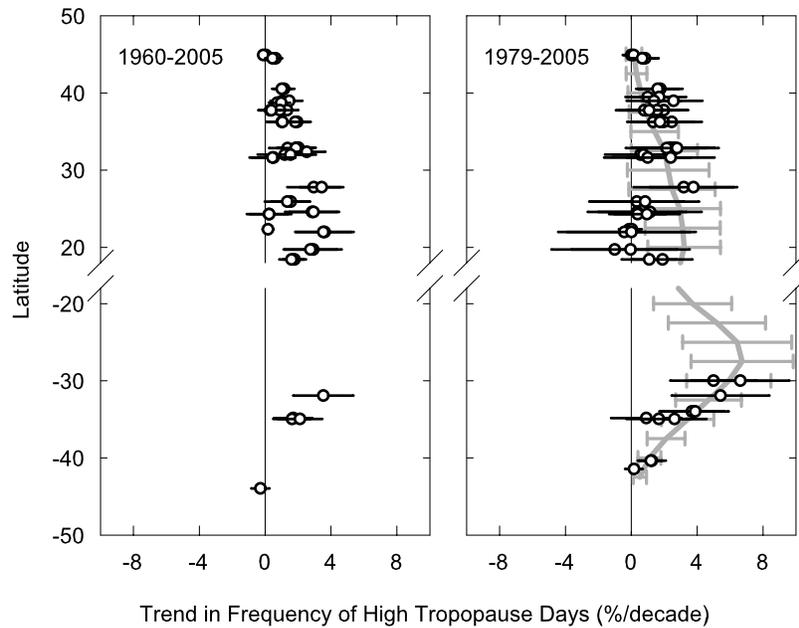


Figure 5. Trends in the frequency of high (>15 km) tropopause days at radiosonde stations between 20 and 45° latitude (left) for 1960 to 2005 and (right) for 1979 to 2005. Figure 5 right shows trends based on zonal mean reanalysis data at 2.5° latitude intervals are shown for 1979 to 2005 (grey curve and error bars). Error bars are $\pm 2\sigma$ confidence intervals.

requirement for this period. The 1960–2005 trends in the NH are very insensitive to this relaxation because most of the NH stations have high-reporting records.

[13] For the radiosonde data, trends are quantified in relative frequency units of percent per decade, where the percent is the ratio of the number of high tropopause days to the total number of observations in a given year. For the reanalysis data, where missing data is not a problem, we use absolute frequency units of days per decade on the basis of the annual number of high tropopause days. All trend confidence intervals are $\pm 2\sigma$ values.

[14] For both data periods the majority of subtropical stations show upward trends in the frequency of tropical tropopause conditions, with increases of typically about 2–6% per decade or increases of about 1–3 weeks of tropical tropopause conditions per decade. Trends for 1960 to 2005 are statistically significant (2σ confidence intervals do not encompass 0) for most stations, but for 1979 to 2005, many of the NH subtropical stations' trends are not. Trends derived from reanalysis data for 1979 to 2005 (Figures 5 right and 6) confirm the general patterns of increases in the frequency of tropical tropopause heights in the subtropics and of stronger trends in the SH subtropics than in the NH. The statistically significant SH trends extend across almost all longitudes, whereas the NH trends are restricted to the subtropical regions over Africa, the North Atlantic, North America, and the easternmost part of the North Pacific basin. The only subtropical region where trends are absent is over the Indian-South Asian area; here the summer circulation is dominated by the monsoon anticyclone [Highwood and Hoskins, 1998], and the number of days per year with tropical tropopause conditions is climatologically high (Figure 4). The discrepancy in NH trend magnitude between the reanalysis and radiosonde data

in Figure 5 is likely due to the lack of radiosonde stations in the North Atlantic and North Africa.

[15] These trends in the number of high/tropical tropopause days in the subtropics of both hemispheres suggest an expansion of the tropical belt. This trend is clearly seen in Figure 7, which shows the poleward migration of the average latitude at which the NCEP/NCAR and ERA40 reanalysis data indicate 100, 200, and 300 d/a had tropopause levels >15 km. In the NCEP/NCAR data the long-

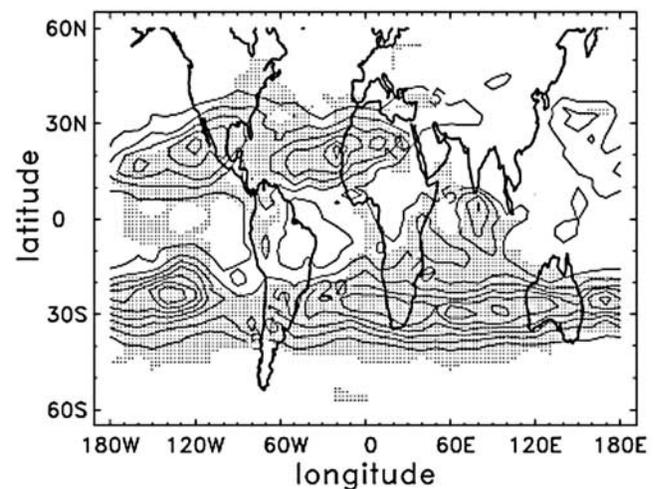


Figure 6. Trends in the number of high tropopause day per year based on NCEP/NCAR reanalysis data for 1979 to 2005. Contour interval is 5 d/decade and all contoured values are positive. Regions of statistically significant trends (based on $\pm 2\sigma$ confidence intervals) are shaded.

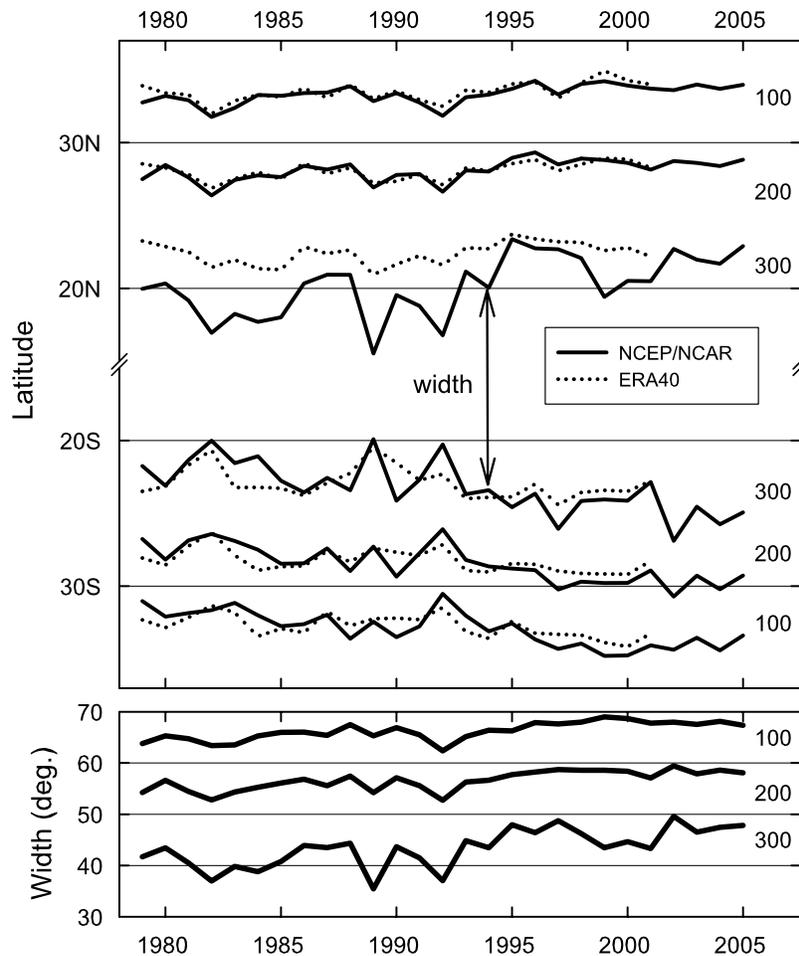


Figure 7. (top) Time series (1979–2005), based on NCEP/NCAR (solid lines) and ERA40 (dotted lines) reanalysis data, of the mean latitudes (averaged over all longitudes) at which 100, 200, and 300 d/a had tropopause levels higher than 15 km. (bottom) The latitudinal width of the tropical belt, as measured by the distance between the NH and SH 300, 200, and 100 d/a isolines from the NCEP/NCAR data.

term poleward trends of the 300 d/a isolines are 1.6° latitude per decade in the SH and 1.5° latitude per decade in the NH, consistent with the approximate trends reported by *Fu et al.* [2006], *Hudson et al.* [2006], and Hu and Fu (submitted manuscript, 2007), and about five times greater than the 0.3° per decade poleward movement of the 300 hPa NH jet stream during 1963–2001 [Angell, 2006]. These trends in the position of the 300 d/a isolines lead to an expansion of the tropical belt of $3.1 \pm 1.4^\circ$ latitude per decade (Figure 7 bottom). Considering the separation of the 200 and 100 d/a isolines as measures of the width of the tropics, we obtain smaller trends of 1.8 ± 0.6 and $1.7 \pm 0.6^\circ$ latitude per decade, respectively.

[16] Figure 7 also shows comparable results from the ERA40 reanalysis for 1979 to 2001. The positions of the SH isolines are in good agreement in the two reanalyses. However, the NH 300 d/a isolines are closer to the equator in NCEP/NCAR than in ERA40, and in both hemispheres, ERA40 shows less interannual variability than NCEP/NCAR.

[17] The NH and SH time series in Figure 7 are anti-correlated. The two 300 d/a latitude time series have

correlation coefficients of -0.86 and -0.69 for the NCEP/NCAR and ERA40 reanalyses, respectively. This suggests that on an interannual basis the tropical belt in the two hemispheres expands and contracts like two lungs inhaling and exhaling in tandem. Regression analysis indicates that the NH 300 d/a isolines move about 1.0 (NCEP/NCAR) or 0.5° (ERA40) per degree movement of the corresponding SH isolines. The two reanalyses are in closer accord for the 200 and 100 d/a isolines, with both showing 0.6 to 0.7° movement of the NH lines per degree movement of the SH lines.

[18] This interannual expansion and contraction of the tropical belt appears to be related to interannual changes in temperature. Using satellite microwave sounding unit tropical (20°N – 20°S) temperature observations [Mears et al., 2003], we find statistically significant ($p < 0.02$) correlations between detrended time series of the width of the tropical belt and tropical lower stratospheric temperature ($r = -0.50$) and midtropospheric temperature ($r = 0.49$), with no significant correlation between the tropospheric and stratospheric temperatures ($r = 0.04$). Here we use the Spearman nonparametric correlation to ensure the result is

resistant to outliers and robust to potentially non-Gaussian data distributions. Whether these temperature changes in the troposphere, stratosphere, or both drive the tropopause changes seen here remains an open question.

5. Summary

[19] Radiosonde and reanalysis data reveal a bimodal distribution of tropopause heights in the subtropics of both hemispheres, between ~ 28 and 40° latitude, with one mode above 15 km (the height of the tropical tropopause) and the other at altitudes of the extratropical tropopause below 13 km. Since 1960 (in the radiosonde data) and since 1979 (in both data sets), the frequency of high/tropical tropopause days per year in the subtropics has increased by about 1–3 weeks per decade. Using the mean latitude experiencing 300 d/a of high tropopause as a delineator of the tropics, the tropical belt has expanded by $3.1 \pm 1.4^\circ$ latitude per decade, with somewhat smaller trends (1.8 ± 0.6 and 1.7 ± 0.6) based on the 200 and 100 d/a locations. The expansion into the SH is more zonally uniform than in the NH, where it appears to be restricted to the western half of the hemisphere. On an interannual basis the SH and NH parts of the tropical belt tend to move poleward and equatorward in tandem. Tropical belt expansion (contraction) is associated with anomalously low (high) tropical lower stratospheric temperatures and anomalously high (low) tropical tropospheric temperatures. This tropopause-based analysis of the width of the tropical belt indicates a $5\text{--}8^\circ$ latitude expansion during 1979–2005.

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