How well do we know recent climate trends at the tropical tropopause?

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[1] The tropical tropopause is a transition layer between the troposphere and stratosphere that influences global climate and atmospheric chemistry. Several studies have reported multidecadal tropical tropopause cooling and have suggested a correlation between observed tropopause temperature and stratospheric water vapor. Our more rigorous examination of the observations shows tropopause trends have greater uncertainty than previously suggested and the cooling may not be statistically significant. We used two approaches to remove time-varying bias effects from cold-point tropopause trends estimated from radiosonde observations. Our results are consistent with expectations from a conceptual model of tropopause changes and could resolve discrepancies between complex climate models and observations.

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1. Introduction

[2] The tropopause is a transition layer between the troposphere and stratosphere. *Sausen and Santer* [2003] and *Seidel and Randel* [2006] recognized that tropopause height changes may be fingerprints of anthropogenic climate change. Other studies have linked tropopause temperature changes to tropospheric warming and stratospheric cooling [*Austin and Reichler*, 2008; *Shepherd*, 2002].

[3] Stratospheric water vapor has strong radiative effects and influences ozone chemistry, so its changes can contribute to temperature [*de F. Forster and Shine*, 1999] and ozone changes [*World Meteorological Organization*, 2007]. Air enters the stratosphere from the troposphere mainly through the tropical tropopause, where extremely low temperatures result in low stratospheric humidity [*Brewer*, 1949]. The temperature sensitivity of saturation water vapor mixing ratio—for example a 15% drop per degree cooling at 190 K [*Rosenlof and Reid*, 2008]—suggests tropopause temperature changes could substantially affect stratospheric water vapor.

[4] Various studies report cooling at the tropical cold-point tropopause (CPT, the point of minimum temperature in a vertical profile) over recent decades. *Randel et al.* [2006] calculated 1979–2004 trends of -0.19 ± 0.07 and -0.61 ± 0.14 K/decade at the nearby 100 hPa and 70 hPa pressure levels, respectively, based on radiosonde observations from six stations. *Rosenlof and Reid* [2008] presented 1980–2003 CPT and 100 hPa temperature time series averaged over 52 radiosonde stations that suggest trends of about -0.5 to -1 K/decade. *Zhou et al.* [2001] estimated 1973–1998 CPT trends of -0.57 ± 0.06 and -1.34 K/decade using two methods and several dozen stations. *Gettelman et al.* [2010] noted that two different reanalysis data sets (representations based on observations assimilated into a fixed weather forecast model) exhibit strong tropical CPT cooling (about -1 to -1.5 K/decade) during 1980–2007. (However, they also state that three other reanalyses they assessed exhibit little or no cooling. They also noted that reanalysis CPT trends are uncertain because the vertically discrete representation of the atmosphere in the underlying models does not allow precise resolution of the cold point.) In addition, the tropopause appears to have cooled abruptly by $\sim 1.5°$ to unusually and persistently low temperatures after 2000 [*Randel et al.*, 2006; *Rosenlof and Reid*, 2008]. Stratospheric water vapor exhibits a correlation with near-equatorial tropopause temperature from the 1990s to the 2000s, including a similar drop at the end of 2000 [*Randel et al.*, 2006; *Rosenlof and Reid*, 2008; *Solomon et al.*, 2010], which may have contributed to a slowing of surface warming [*Solomon et al.*, 2010].

[5] Tropical tropopause height and pressure exhibited an increase and decrease, respectively, over the past few decades, e.g., -1.05 hPa/decade over 1979–1997 using the NCEP reanalysis [*Santer et al.*, 2003] and ~ 20 m/decade and ~ -0.5 hPa/decade over 1978–1997 using radiosonde data [*Seidel et al.*, 2001]. *Sivakumar et al.* [2011] found no significant trend in tropical tropopause height over the shorter period of 1998–2008 based on 6 Southern Hemisphere stations.

[6] However, previous studies may have overstated the certainty of CPT trends. Climate records, including radiosonde temperature, height, and pressure data, contain

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inhomogeneities, or time-varying biases, caused by changes in instruments and measurement practices [*Gaffen*, 1994; *Seidel and Randel*, 2006], which complicate trend estimation. Reanalyses are affected by the radiosonde and other observations assimilated [*Gettelman et al.*, 2010; *Haimberger et al.*, 2008]. Inhomogeneity removal tends to reduce stratospheric cooling trends and increase tropospheric warming; unadjusted data show spurious cooling due to reduction over time of biases caused by solar heating of temperature sensors, introduction or modification of radiation and lag corrections, etc. [*Gaffen*, 1994; *Lanzante et al.*, 2003a] Attempts to remove inhomogeneities [*Free et al.*, 2005; *Haimberger*, 2007; *Haimberger et al.*, 2008; *Lanzante et al.*, 2003b; *Sherwood et al.*, 2008; *Thorne et al.*, 2005] have produced adjusted radiosonde temperature data only at fixed pressure levels, e.g., 100 and 70 hPa. Since tropopause pressure varies, most previous tropopause trend studies used unadjusted data. *Zhou et al.* [2001] did remove certain inhomogeneities using a simple multiple regression model, although data quality remains an issue, as discussed below. *Randel et al.* [2006] attempted to minimize the impact of inhomogeneities in analyzing 1992–2005 CPT temperatures by avoiding stations with large step changes relative to Microwave Sounding Unit (MSU) satellite data. However, MSU samples a deep layer surrounding the CPT and the data contain their own inhomogeneities [*Free and Seidel*, 2007].

[7] The reported CPT cooling is problematic. First, it appears inconsistent with a possible long-term stratospheric water vapor increase prior to ~2000 suggested by limited observations [*Zhou et al.*, 2001; *Fueglistaler and Haynes*, 2005; *Hurst et al.*, 2011]. Second, most coupled chemistry and climate models (CCMs) do not simulate strong CPT cooling over recent decades: the mean trend over 18 CCMs was not significantly different from zero in a recent intercomparison [*Gettelman et al.*, 2010]. But, again, the limited vertical resolution of models introduces uncertainty into the CPT calculations.

[8] We present CPT trends calculated using 38–46 tropical radiosonde stations with relatively complete records since 1970. We also relate CPT trends to trends at nearby pressure levels, because some studies have used 100 hPa as a tropical tropopause surrogate [e.g., *Solomon et al.*, 2010] though tropical CPT pressures are less than 100 hPa on average. Our two approaches for adjusting CPT trends were: 1) the "Nearby Level" approach, which compares temperature trends at the CPT and at nearby fixed pressure levels in unadjusted data with trends at those fixed levels in five adjusted data sets, and 2) the "Day-Night Difference" approach, comparing CPT temperature, height, and pressure trends for different times of day.

2. Methods

2.1. Data Sets and Data Selection

[9] Atmospheric data for this study are from an unadjusted quality-controlled radiosonde data set, IGRA [*Durre et al.*, 2006], and several independently adjusted radiosonde temperature data sets: RATPAC [*Free et al.*, 2005], HadAT [*Thorne et al.*, 2005], RAOBCORE [*Haimberger*, 2007], RICH [*Haimberger et al.*, 2008], and IUK [*Sherwood et al.*, 2008]. RATPAC incorporates adjustments developed by *Lanzante et al.* [2003b], involving objective criteria, station history information, and subjective expert judgment to identify and remove inhomogeneities in a small network. We use version RATPAC-B data for individual stations, with no adjustments after 1997. HadAT (version HadAT2) adjusts data using neighboring stations to identify inhomogeneities and maintain spatial and temporal consistency and extends through 2010. RAOBCORE uses information from a reanalysis to locate and adjust temporal discontinuities, and RICH uses these same change points but determines adjustments using neighboring stations. RAOBCORE and RICH include very few adjustments after 2005. IUK involved an iterative approach and a statistical model to identify artificial step changes; data are available through February 2006. All these data sets begin before our analysis period, 1970–2010.

[10] We focus on the cold-point tropopause (CPT) in this analysis rather than the lapse-rate tropopause (LRT) because it is more relevant for stratospheric water vapor. In the tropics, the CPT is typically ~0.5 km and ~10 hPa higher and <1 K colder than the LRT [*Seidel et al.*, 2001]. We think any differences in the long term behavior of the LRT compared to the CPT will probably be minor, given the closeness in height and temperature of the LRT and CPT and the simpler structure of the tropopause region in the tropics than at higher latitudes. This issue could be examined in a future study. Also note that we diagnosed the CPT height using unadjusted temperature profiles. Temperature adjustments could change the location of the CPT in a profile, possibly upward for earlier years, and weaken an apparent increasing trend in CPT height. But in practice, adjusted temperature data are available only on a set of widely spaced fixed pressure levels, and the majority of the adjusted data sets come at monthly resolution, so they could not provide information on individual soundings.

[11] We considered only those stations that exist in both the IGRA and RAOBCORE data sets. For inclusion in the analysis, soundings and station data also met the following criteria. Soundings have at least eight data levels and reach at least 70 hPa. If there was more than one temperature minimum, CPT was taken to be the one at the highest pressure, corresponding to the lowest saturation water vapor mixing ratio. At least 10 daily observations were required to calculate a monthly mean for the CPT or a particular pressure level, separately for the 00Z and 12Z observation times. A minimum of three occurrences of each calendar month at a station (e.g., Jan. 1971, Jan. 1974, and Jan. 1995) was required to generate a mean annual cycle (for the base period 1971–1997) for calculating monthly anomalies. We then omitted the time series for a given station and observation time if more than one third of the CPT monthly anomalies were missing during a particular analysis period. In the main analysis, time series missing more than one third of the months during the first or last year, i.e., 1979 or 2005, were also omitted.

[12] These criteria resulted in the station network shown in Figure 1 and Table 1, although HadAT, and especially RATPAC, do not include all of these. Because stations unevenly sample the tropics, tropical average time series are based on the average of three equal-size longitude regions (Figure 1), each computed by averaging station time series. Regional average time series are computed separately for 00Z and 12Z, which are then combined with equal weights.

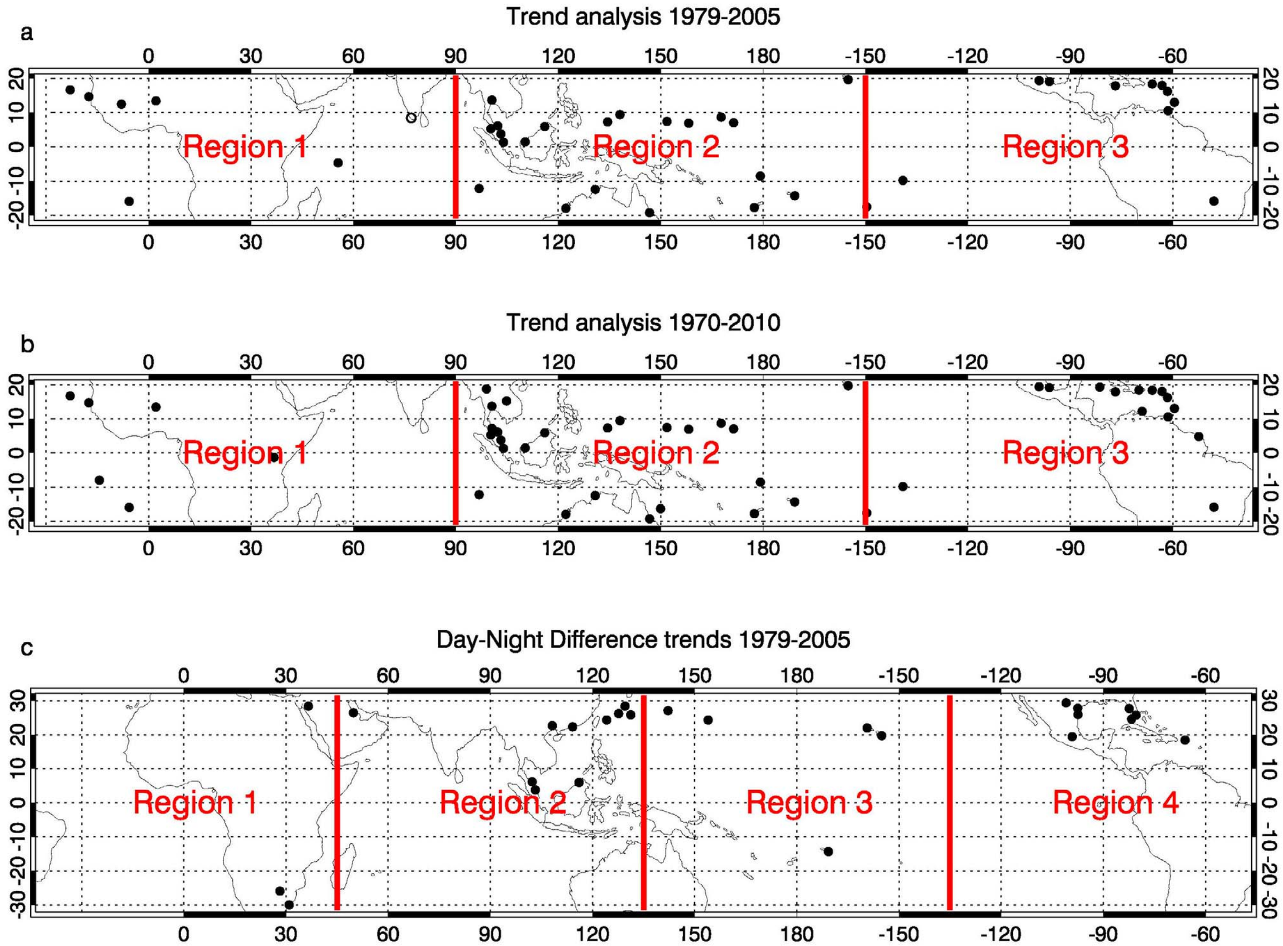

Figure 1. Maps of stations used and region boundaries for (a) 1979–2005 trend analysis, (b) 1970–2010 time series and sliding trends (for this period, the restriction that station time series must have sufficient data during the beginning and end years was relaxed), and (c) 1979–2005 Day-Night Difference trend analysis. The station Thiruvananthapuram in India (unfilled circle in Figure 1a) was used in a sensitivity study and not in the main analysis. Note that HadAT and especially RATPAC do not include all the stations shown in these maps.

2.2. Trend Calculations

[13] Trends were calculated using least squares linear regression, with standard errors that account for autocorrelation [*Santer et al.*, 2000]. We also used a non-parametric median of pairwise slopes method [*Lanzante*, 1996] and found very similar results (not shown). Uncertainties in adjusted CPT trends are estimated as the square root of the sum of variances of the addends (assumed uncorrelated), discussed below. Statistical significance is based on Student's t test at the 95% level.

[14] The Nearby Level approach to adjusting CPT trends involved adding the 100 or 70 hPa trend calculated from an adjusted radiosonde data set and the trend in the time series of differences between the CPT and the fixed level (the latter two are based on unadjusted data). This assumes that the CPT trend can be estimated from the adjusted trend at a fixed level. We verified that inhomogeneities at the CPT generally occur at the same time as those at the surrounding levels and are of an intermediate magnitude by visual inspection of time series (not shown).

[15] The Day-Night Difference approach is based on the same principles as methods employed previously to homogenize radiosonde temperature data [*Lanzante et al.*, 2003b; *Sherwood et al.*, 2005; *Sherwood et al.*, 2008]. We apply the approach to CPT variables, calculating trends in the difference between 12Z and 00Z time series for four longitudinal regions (Figure 1c). In the regions surrounding the 0° and 180° meridians, the 00Z and 12Z times correspond to local midnight and midday or the reverse. Thus, these two regions should exhibit the largest trends in the difference between unadjusted 12Z and 00Z temperatures, because a major contributor to inhomogeneities, solar heating of temperature sensors, varies with solar elevation angle and therefore with local time. To remove the effect of solar heating-related inhomogeneities, we assumed nighttime observations are free of inhomogeneities and therefore the trend in 12Z-00Z represents a spurious trend that can be subtracted from the daytime trend; real trends in the day-night difference are negligible [*Sherwood et al.*, 2005]. Since local observation times within 45°E–135°E and 135°W–45°W are far from midday and midnight (so the solar heating effect cannot be estimated through our approach), we applied an adjustment to the 00Z and 12Z

Table 1. Radiosonde Stations Used in This Study

Station	Latitude	Longitude	WMO ID	Analysis[a]
Durban Airport	−29.97	30.95	68588	c
Pretoria/Irene	−25.92	28.22	68263	c
Townsville	−19.25	146.77	94294	ab
Broome Airport	−17.95	122.23	94203	ab
Nadi Airport	−17.75	177.45	91680	ab
Tahiti-Faaa	−17.55	−149.62	91938	ab
Willis Island	−16.30	149.98	94299	b
St. Helena Island	−15.93	−5.67	61901	ab
Brasilia Aeroporto	−15.87	−47.93	83378	ab
Pago Pago/Tafuna	−14.33	−170.72	91765	abc
Darwin	−12.43	130.87	94120	ab
Cocos Island	−12.18	96.83	96996	ab
Atuona	−9.80	−139.03	91925	ab
Funafuti	−8.52	179.22	91643	ab
Ascension Is./ Wideawake	−7.97	−14.40	61902	b
Seychelles Airport	−4.67	55.53	63985	a
Nairobi/Dagoretti	−1.30	36.75	63741	b
Singapore/Changi	1.37	103.98	48698	ab
Kuching	1.48	110.33	96413	ab
Kuantan	3.78	103.22	48657	abc
Cayenne/ Rochambeau	4.83	−52.37	81405	b
Penang/Bayan Lepas	5.30	100.27	48601	ab
Kota Kinabalu	5.95	116.05	96471	abc
Kota Bharu	6.17	102.28	48615	abc
Ponape	6.97	158.22	91348	ab
Majuro Atoll	7.08	171.38	91376	ab
Songkhla	7.20	100.60	48568	b
Koror	7.33	134.48	91408	ab
Chuuk	7.47	151.85	91334	ab
Thiruvananthapuram	8.48	76.95	43371	d
Kwajalein Atoll	8.73	167.73	91366	ab
Yap	9.48	138.08	91413	ab
Port of Spain/Piarco	10.58	−61.35	78970	ab
Plesman Field	12.20	−68.97	78988	b
Bamako/Senou	12.53	−7.95	61291	a
Grantley Adams International Airport	13.07	−59.50	78954	ab
Niamey-Aero	13.48	2.17	61052	ab
Bangkok	13.73	100.57	48455	ab
Dakar/Yoff	14.73	−17.50	61641	ab
Ubon Ratchathani	15.25	104.87	48407	b
Le Raizet	16.27	−61.53	78897	ab
Sal Island	16.73	−22.95	08594	ab
Kingston/Norman Manley	17.93	−76.78	78397	ab
Juliana	18.05	−63.12	78866	ab
San Juan	18.43	−66.00	78526	abc
Santo Domingo	18.47	−69.88	78486	b
Chiang Mai	18.78	98.98	48327	b
Vera Cruz/Hacienda	19.15	−96.12	76692	ab
Grand Cayman Is./ Roberts	19.30	−81.37	78384	b
Mexico City	19.43	−99.13	76679	abc
Hilo/Lyman	19.72	−155.07	91285	abc
Lihue	21.98	−159.35	91165	c
King's Park	22.32	114.17	45004	c
Nanning	22.63	108.22	59431	c
Marcus Is.	24.30	153.97	47991	c
Ishigakijima	24.33	124.17	47918	c
Key West	24.58	−81.70	72201	c
Miami	25.75	−80.38	72202	c
Minamidaito Jima	25.83	131.23	47945	c
Brownsville	25.92	−97.42	72250	c
Naha	26.20	127.68	47936	c
King Fahd Airport	26.44	49.81	40417	c
Chichi Jima	27.08	142.18	47971	c
Tampa	27.70	−82.38	72210	c
Corpus Christi	27.78	−97.51	72251	c
Tabouk	28.37	36.58	40375	c
Naze	28.38	129.55	47909	c
Del Rio	29.37	−100.92	72261	c

[a]These codes correspond to the panels in Figure 1, i.e., "a" indicates the station was used in the 1979–2005 trend analysis, "b" refers to the 1970–2010 analyses, "c" refers to the 1979–2005 Day-Night Difference trend analysis, and "d" indicates that the station was used only in a sensitivity test.

observations in these regions equal to one-half of the average spurious trend over the other two regions. (The factor of one-half approximates the effects of solar elevation angles at these longitudes at 00Z and 12Z that are neither near zenith nor near nadir.) We also did a calculation applying no adjustment to the 45°E–135°E and 135°W–45°W regions, as a lower bound to the estimated solar heating effect (results not reported). Tropical-average adjustments in this case are in the same direction as, but smaller than, those resulting from adjustments to data in all longitude regions.

[16] For this Day-Night Difference analysis, we expanded the latitude range to 30°S–30°N (Figure 1c and Table 1) to enlarge the sample of stations with data at both observation times. The expanded latitudinal range was only used to estimate the solar heating effect, which should be similar throughout this range [*Sherwood et al.*, 2005]. Reported adjusted tropical-average trends are for 20°S–20°N.

3. Results

3.1. Time Series

[17] Figure 2 shows monthly time series of tropical-average tropopause variables from unadjusted and adjusted data sets. Unadjusted 100 hPa, CPT, and 70 hPa temperatures exhibit substantial correlation and long-term cooling (Figure 2a). Cooling increases from 100 hPa to the CPT to 70 hPa, consistent with the average tropical CPT location between 100 and 70 hPa [*Seidel et al.*, 2001]. In Figure 2b, CPT height increases over time, CPT pressure decreases, and the two are strongly anti-correlated, as expected. CPT height and pressure are negatively and positively correlated with temperature, respectively, although their long-term behaviors diverge after data adjustments, as shown later. In Figures 2c and 2d, adjusted data sets all exhibit less cooling at 100 and 70 hPa than the unadjusted data set. Quantitative trend results are in section 3.2.

[18] The previously reported temperature drop at the end of 2000, linked to a concurrent increase in stratospheric upwelling [*Randel et al.*, 2006; *Rosenlof and Reid*, 2008], is evident in each data set, but it does not seem unusual in the context of the overall analysis period. The years after 2000 are relatively cold, but so are 1995–1997, even after removal of the inhomogeneity associated with a 1995 instrument switch at some U.S.-operated Pacific stations (including four in our analysis) [*Lanzante*, 2009]. Neither are the high CPT Z and low p values after 2000 unprecedented. Thus, tropical-average CPT characteristics during the last decade may be less unusual than previously suggested [*Randel et al.*, 2006; *Rosenlof and Reid*, 2008; *Solomon et al.*, 2010].

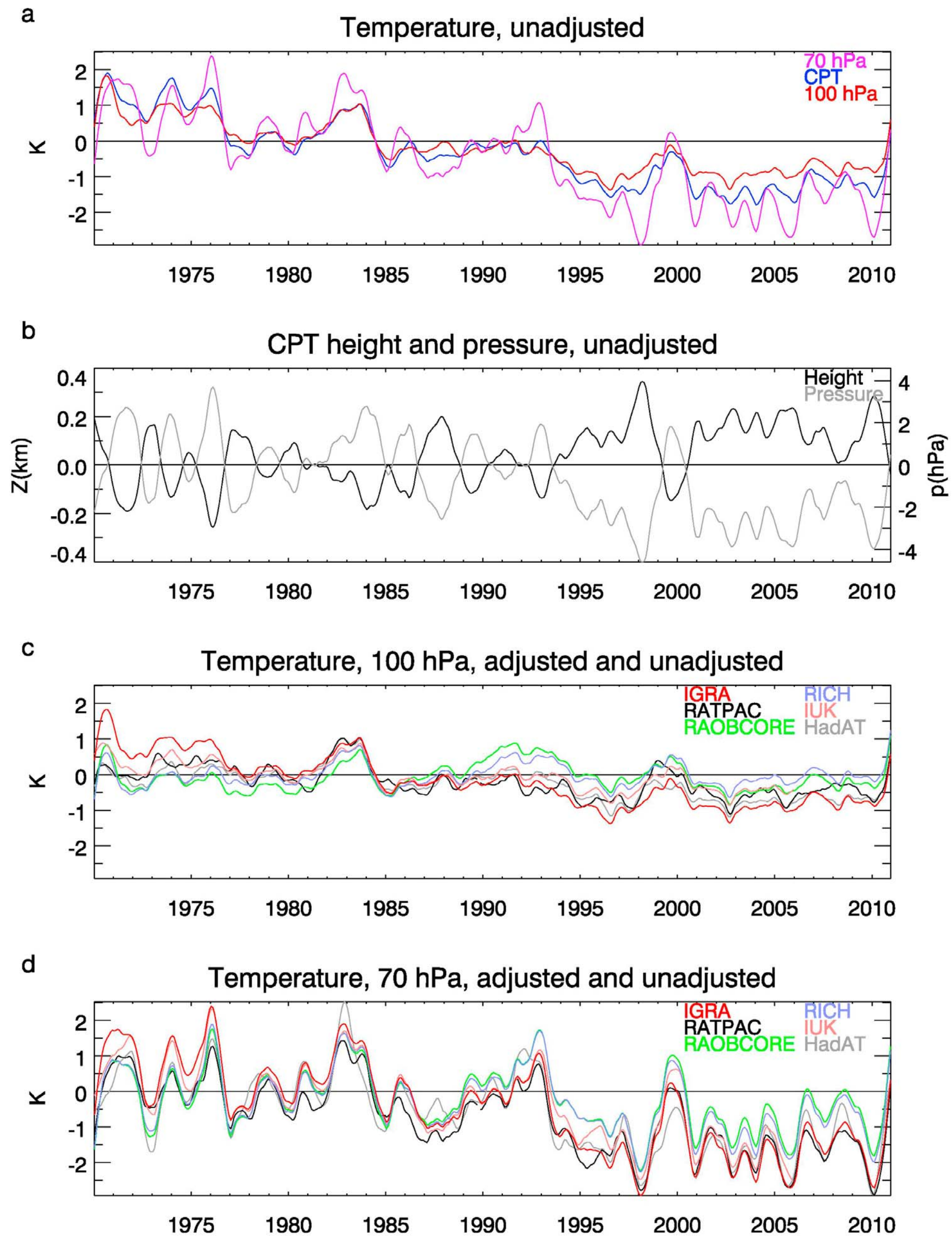

Figure 2. Monthly anomaly time series for tropopause variables, averaged over 20°S–20°N and over 00Z and 12Z. (a) Temperature at the CPT, 100 hPa, and 70 hPa from the unadjusted data set (IGRA). (b) Geopotential height and pressure at the CPT from IGRA. Temperature from IGRA and adjusted data sets (c) at 100 hPa and (d) at 70 hPa. Time series are smoothed using an FFT low-pass filter (cutoff of 0.5 yr^{-1}). Note data are not adjusted beyond ~2005 for RAOBCORE and RICH and 1997 for RATPAC-B; IUK ends in 2006.

3.2. Unadjusted and Adjusted Trends

[19] Figure 3 shows estimated linear tropical average temperature trends at different levels over 1979–2005 (for comparison with previous analyses [*Randel et al.*, 2006; *Rosenlof and Reid*, 2008]). Trends from unadjusted data are statistically significant and consistently more negative than those from adjusted data sets at the same level (Figure 3a). RATPAC, RAOBCORE, and RICH adjusted data do not show significant 100 hPa cooling. Again, the CPT exhibits greater cooling than the 100 hPa level and less than the 70 hPa level (Figure 3a). Trends for CPT height and pressure (not shown) over the same period based on unadjusted data are 91 $\pm$ 49 m/decade and -1.7 ± 0.7 hPa/decade, respectively.

[20] Our Nearby Level approach yields a wide range of CPT temperature trend estimates, from -0.64 ± 0.21 to -0.23 ± 0.17 K/decade (using 100 hPa data from HadAT and RICH, respectively) (Figure 3b), suggesting substantial uncertainty in the CPT temperature trend. Furthermore, all estimates are less negative than the unadjusted trend, -0.78 ± 0.26 K/decade.

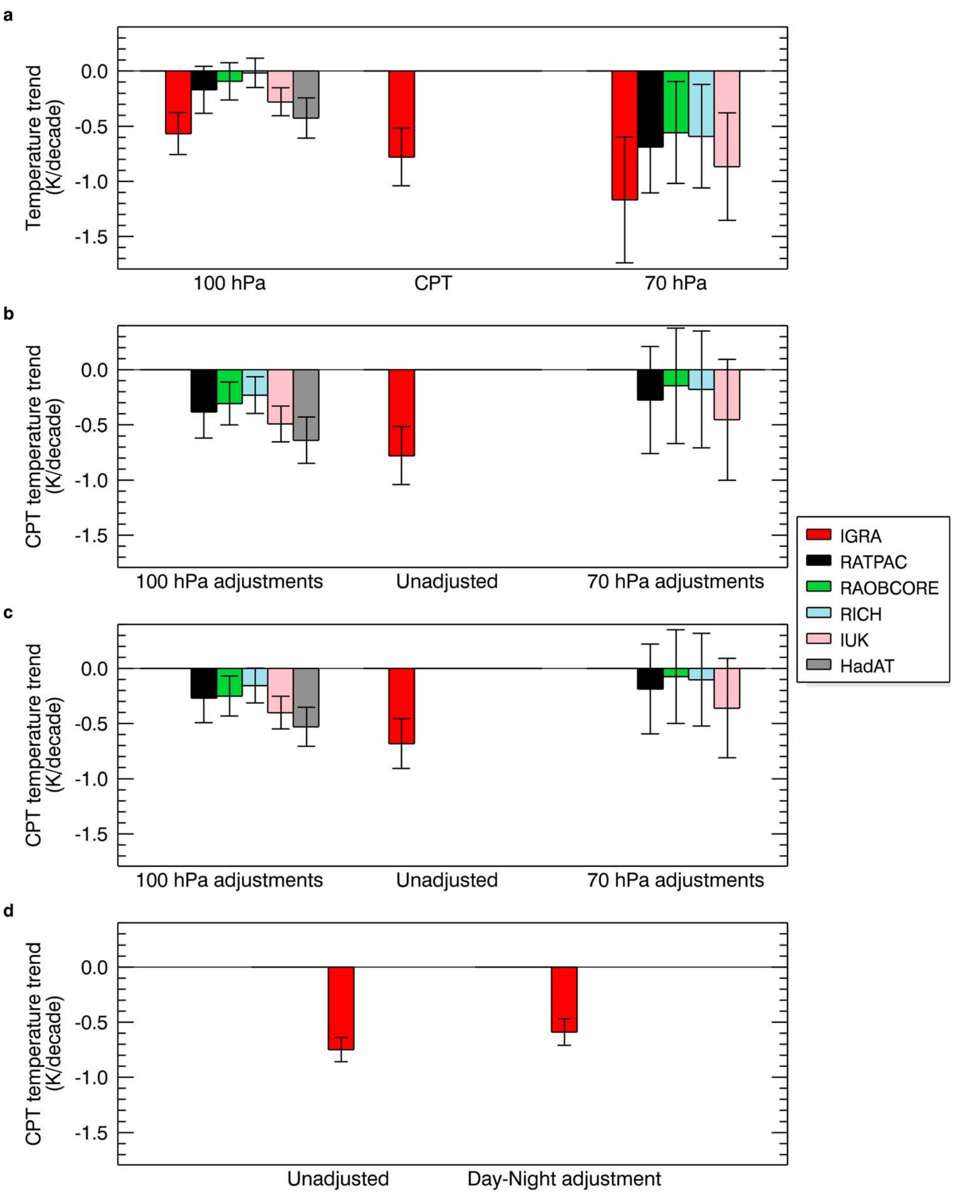

Figure 3. Estimates of tropical average (20°S–20°N) temperature trends during 1979–2005. (a) Trends at the CPT and nearby pressure levels in the unadjusted data set, and at fixed pressure levels in the adjusted data sets; (b) CPT trends adjusted for inhomogeneities through the nearby Level approach using 100 hPa and 70 hPa data; (c) same as Figure 3b but excluding volcanically influenced periods; and (d) unadjusted and adjusted CPT trends in the day-night difference approach. Error bars represent 95% confidence intervals. Data at 70 hPa are not available for HadAT.

Confidence intervals for CPT trends estimated from 70 hPa data even encompass zero, due in part to the fact that greater temporal variability in 70 hPa temperatures compared to that at 100 hPa results in larger uncertainties in the adjusted CPT trends based on the former.

[21] There is wide variation in adjusted CPT temperature trends calculated for individual longitudinal regions for some of the data sets (not shown). However, one should not attach too much significance to differences in trend among regions in our analysis, since each of the regional trends is calculated from a relatively small number of stations. Region 1 (as defined in Figure 1) has no observations whatsoever at the 00Z time. This contributes to large uncertainties in the Region 1 trends, especially for RATPAC, which has only one station (Dakar) in this region.

[22] Large volcanic eruptions can lead to sizable short-term warmings in the lower stratosphere (especially visible in the 70 hPa time series in Figure 2) that may affect estimates of trends and their uncertainties. We tested the effect of the warmings following the El Chichón (April 1982) and Mt. Pinatubo (June 1991) eruptions by excluding from the trend analysis data within two years after those eruptions. The resulting CPT temperature trends over 1979–2005 (Figure 3c) are similar to the original ones (Figure 3b), even a little closer to zero, and the error bars are also similar to the original ones, in some cases slightly smaller. The basic

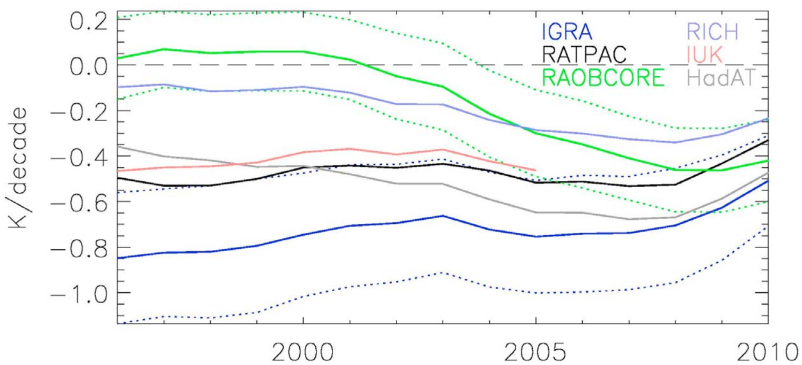

Figure 4. Tropical average CPT temperature trends based on unadjusted and adjusted data sets for sliding 27-year periods. Trends are plotted by the last year of the period. The first period shown is 1970–1996, and the last 1984–2010; observations are sparse prior to the 1970s. Adjusted CPT trends are derived from adjusted 100 hPa trends using the Nearby Level approach. Dotted lines depict 95% confidence intervals (only shown for IGRA and RAOBCORE).

conclusions—that there is a wide range of estimated trends and that some of them are not significantly different from zero—are unaffected.

[23] That the recent temperature trend estimated from the adjusted data sets is less negative than the unadjusted trend is a robust result over various 27-year periods between 1970 and 2010 (Figure 4). The confidence intervals for the CPT trend estimates based on RAOBCORE and RICH encompass zero for some periods up to 2003 (not shown for RICH). Although RAOBCORE-based estimates exhibit positive values up to 2001, they are not statistically significant, and the other data sets exhibit no positive 27-year trends. Thus, our estimated CPT temperature trends still seem inconsistent with stratospheric water vapor observations indicating an increase before 2000 [*Fueglistaler and Haynes*, 2005; *Hurst et al.*, 2011; *Zhou et al.*, 2001].

[24] Our Day-Night Difference approach to estimating CPT trends assumes that a trend in daytime-nighttime difference is spurious and related to solar heating of temperature sensors. The regions surrounding the 0° and 180° meridians (45°W–45°E and 135°E–135°W) indeed exhibit the largest (most negative or positive) trends in 12Z-00Z unadjusted temperature difference, as discussed in Methods (Figure 5a). In contrast, the adjusted data sets exhibit less contrast among regions, because inhomogeneities related to solar heating have mostly been removed.

[25] Difference trends for CPT height exhibit a similar longitudinal pattern to those for CPT temperature (Figure 5b). This is not surprising, as geopotential height is a derived quantity that is proportional to vertically averaged temperature in the underlying layer [*Seidel and Randel*, 2006]. For CPT pressure, there is no contrast between the difference trends in the regions surrounding 0° and 180° and those in the other two regions (Figure 5c). Although pressure measurements appear not to be affected by diurnal effects, they may be subject to other inhomogeneities [*Seidel and Randel*, 2006].

[26] The Day-Night Difference approach yields a tropical-average adjusted CPT temperature trend of -0.59 ± 0.12 K/decade, compared to an unadjusted trend of -0.75 ± 0.11 K/decade (Figure 3d). (Note that the unadjusted trend here is slightly different from that estimated in the Nearby Level analysis because of the averaging of four longitudinal regions rather than three.) The adjustment is smaller than the adjustments from our Nearby Level approach (except for the one based on HadAT) (Figure 3b), because the Day-Night Difference approach addresses only solar heating effects.

[27] For CPT height, the adjusted trend is 109 ± 18 m/decade; the unadjusted trend is 99 ± 17 m/decade. The tropopause may have been rising 10% *more* than suggested by unadjusted radiosonde data during 1979–2005. The explanation is that since geopotential height is proportional to temperature in the underlying layer, spurious decreases in temperature should result in spurious decreases in height. Thus, removing those spurious decreases results in a larger positive height trend.

[28] Our estimated trends in temperature, height, and pressure are not very sensitive to the inclusion of any particular station except for one outlier, Thiruvananthapuram (formerly Trivandrum), India, which we omitted in the above analysis. The station is the only one we considered that exhibits decreasing CPT height and increasing pressure during 1979–2005 and it exhibits anomalously large cooling. In addition, previous studies had found the radiosonde data from Indian stations generally problematic for trend analysis [*Parker et al.*, 1997]. Including Thiruvananthapuram increases the unadjusted tropical CPT cooling from -0.78 K/decade to -1.02 K/decade. This result is especially sensitive to the Indian station since one of the three regions that we used to compute the tropical average, Region 1, contains only this one station for the 00Z time. The spatially and temporally uneven sampling is an unavoidable consequence of a radiosonde data set that has relatively few long-term records in the tropics. The inclusion of problematic stations could have contributed to the large cooling trends inferred by some previous studies, especially *Zhou et al.* [2001], which included both Thiruvananthapuram and other stations that we omitted because of excessive data gaps.

[29] We assessed two sources of inhomogeneities that may not have been explicitly accounted for in existing adjusted data sets: an artificial minimum cutoff of readings at −90.1°C during 1989–1999 and a switch to stronger balloons in 1998 at U.S.-operated stations (see Appendix A). We concluded that neither substantially affects our tropical trend analysis.

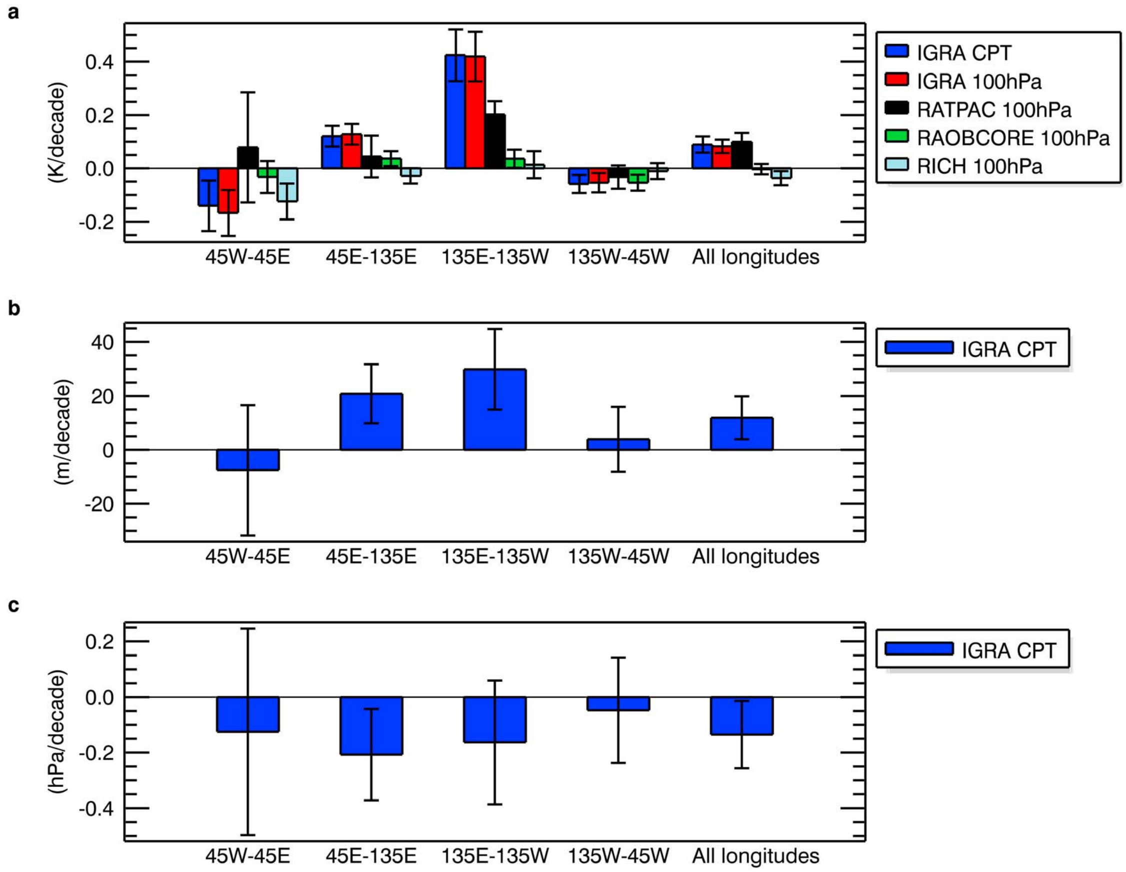

Figure 5. Regional average 1979–2005 trends in 12Z-00Z differences for (a) temperature, (b) geopotential height, and (c) pressure. The HadAT and IUK data sets are not included since they do not provide separate data for 00Z and 12Z. Error bars represent 95% confidence intervals.

3.3. Conceptual Model

[30] The increasing CPT height and the large uncertainty in our CPT temperature trend estimate are consistent with expectations from a simple conceptual model of the tropopause [*Austin and Reichler*, 2008; *Shepherd*, 2002], in which the tropopause is located where tropospheric and stratospheric temperature profiles with lapse rates of opposite sign intersect. Tropospheric and stratospheric temperature changes (anthropogenic or natural) drive changes in tropopause height and temperature via simple geometric relationships, with observed stratospheric cooling and tropospheric warming having competing effects on CPT temperature but acting in concert to raise the CPT, replicating behavior seen in more complex climate models [*Shepherd*, 2002]. The model implies that the sign of the CPT temperature trend over recent decades may not be certain, whereas an increase in the CPT height is to be expected. Results of quantitative tests in which we substituted observed stratospheric and tropospheric temperature trends (derived from the suite of adjusted radiosonde data sets) and plausible parameter values into model equations derived by *Staten and Reichler* [2008] indicate that both warming and cooling are possible at the CPT, while the model predicts an increase in height for all cases considered. Although this very simple model does not treat the complex dynamical and radiative processes that shape the tropical tropopause in the real world, it is still useful for illustrative purposes, as demonstrated also by *Austin and Reichler* [2008].

4. Conclusions

[31] The wide range of estimates we obtained for recent tropical CPT temperature trends based on an ensemble of adjusted radiosonde data sets suggests that the trends are less certain than previous studies imply. Furthermore, the confidence intervals that encompass zero (for 1979–2005 CPT trends estimated from 70 hPa adjusted data and for trends up to the early 2000s estimated from some of the 100 hPa adjusted data) suggest that the CPT may not have experienced significant long-term cooling. In contrast, CPT height has possibly increased more than previously thought. Both a cooling and a warming (or lack of cooling) at the CPT are physically plausible considering the competing influences of tropospheric warming and stratospheric cooling; in contrast, a CPT height increase would very much be expected since both tropospheric warming and stratospheric cooling act in that direction. An overestimate of CPT cooling in some reanalyses, possibly related to the assimilation of unadjusted radiosonde data, could explain, at least in part, an apparent discrepancy between these data sets and CCMs. Note that one reanalysis that does not exhibit a significant CPT temperature trend, ERA-Interim, assimilates adjusted radiosonde data [*Dee et al.*, 2011].

[32] Understanding actual variations in stratospheric water vapor might require analysis of the spatial and seasonal details of tropopause trends. For example, the moist phase in the annual cycle of water vapor mixing ratio in air entering the stratosphere occurs in boreal summer and is influenced predominantly by tropopause conditions in a limited region, namely South and Southeast Asia [*Wright et al.*, 2011]. Analyses of seasonal variations in temperature trends at fixed pressure levels near the CPT [*Free*, 2011; *Randel et al.*, 2009] suggest that tropical CPT temperature trends may also vary seasonally.

[33] Possible causes of an increase in stratospheric water vapor before 2000 despite decreasing or stable CPT temperatures include long-term changes in the locations or seasons in which water vapor is transported into the stratosphere [*Rosenlof et al.*, 2001] and trends in small-scale processes such as cross-tropopause deep convection and associated re-evaporation of lofted ice in the stratosphere [*Liu et al.*, 2010; *Nielsen et al.*, 2011; *Schoeberl and Dessler*, 2011; *Steinwagner et al.*, 2010] rather than slow, large-scale ascent through the CPT. Remaining inhomogeneities in adjusted temperature data [*Haimberger et al.*, 2008; *Sherwood et al.*, 2008] could also contribute to the discrepancy between expected and observed water vapor trends.

Appendix A: Sensitivity to Temperature Cutoff and Switch to Stronger Balloons

[34] We assessed the potential effect of two relatively recent inhomogeneities, namely the imposition of an artificial $-90.1°$C cutoff for temperature readings at U.S.-operated stations during 1989–1999 and a switch to balloons better suited to high-altitude use in 1998 at U.S. Pacific stations [*Elliott et al.*, 2002]. The first change could distort temperature measurements especially at stations in the Western Pacific, where CPT temperatures are most likely to reach that extremely low level. The second change could result in a sampling bias as earlier balloons have a greater tendency to burst at relatively low altitudes when temperatures are cold and may thus miss the CPT; the issue of sampling biases due to balloon burst has been discussed qualitatively before [*Parker and Cox*, 1995] but not with respect to tropopause sampling. Since we filter out the soundings that do not reach 70 hPa or lower pressure, the switch to stronger balloons implies that more soundings could potentially pass our filter, creating a sampling bias.

[35] To test sensitivity to the $-90.1°$C cutoff, we considered a scenario in which the CPT temperature would have dropped below the cutoff by increasing margins during 1989–1999, for two test stations, Chuuk and Majuro. We thus created hypothetical adjusted time series where we subtracted increasingly large quantities (ranging from 0 to 4 K) from all data points between 1989 and 1999 that reached the cutoff. Since relatively few points reach the cutoff, we found that the effect of the adjustments on monthly means is small, <0.5 K. The effect on monthly anomalies is even smaller (since the mean annual cycle is also affected); plotted original and adjusted time series are barely distinguishable from each other. The effect on long-term trends is insignificant.

[36] To evaluate the second potential inhomogeneity, we examined the maximum altitude attained by each sounding at some of the affected stations (Chuuk, Majuro, and Pago Pago) and found that there indeed appears to be an increase in the maximum heights on average after 1998. However, we did not find a clear correlation between minimum sounding temperatures and maximum heights before 1998. (Here we disregarded soundings that did not reach $\sim$16 km or $\sim$110 hPa, as they are associated with relatively warm temperatures and their termination is probably unrelated to cold-induced balloon burst.) There is thus no indication that the coldest atmospheric temperatures eluded observation due to premature balloon burst, suggesting that the switch to higher flying balloons did not shift the temperature distribution. We conducted an additional test in which the affected stations (consisting of Lihue, Hilo, Chuuk, Ponape, Kwajalein, Majuro, Koror, Yap, and Pago Pago in our analysis) were omitted from the trend calculations. The resulting regional and tropic-wide trends for temperature and other variables at the CPT and nearby pressure levels are only slightly different from those that include the affected stations, e.g., -0.81 versus -0.78 K/decade for the IGRA tropical average CPT temperature trend and -0.39 versus -0.43 K/decade for the HadAT 100 hPa temperature trend. We conclude that any potential inhomogeneity caused by the balloon switch at U.S. operated stations does not substantially affect our trend analysis.

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