The Seasonal Structure of Temperature Trends in the Tropical Lower Stratosphere

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ABSTRACT

Radiosonde data show a large seasonal difference in trends since 1979 in the tropical lower stratosphere, with a maximum cooling of ~1 K decade^{-1} in December and January and a minimum in March or April at 50 mb between 10°N and 10°S. The statistically significant difference of up to ~1 K decade^{-1} between trends in December and those in March amounts to up to 20% of the climatological seasonal cycle. Although the size of annual mean cooling trends differs substantially among datasets, the seasonal pattern of trends is similar in all six radiosonde datasets used here and is consistent with MSU satellite data for the lower stratosphere. This greater cooling in boreal winter essentially disappears below 100 mb, and the troposphere has a different and smaller seasonal trend pattern.

Trends in the tropical stratosphere show an inverse relationship with those in the Arctic for 1979–2009, which might be related to changes in stratospheric circulation. In most radiosonde data, however, the seasonal pattern of tropical trends at 50 mb since 1979 seems to come from a seasonal difference in the size of the stratospheric cooling in the mid-1990s, and trends for longer time periods or those for 1995–2009 do not show the same seasonal dependence. Whether the strengthening of the seasonal cycle in the stratosphere represents a long-term change related to greenhouse gas forcing, a shorter-lived shift related to ozone depletion or unforced interdecadal variability requires careful further study.

1. Background

Seasonal patterns in temperature trends could be an important indicator for climate change detection and attribution studies in the stratosphere (Ramaswamy et al. 2001). The strong seasonal dependence of stratospheric temperature trends in the Antarctic, with strong ozone-related cooling in austral spring and summer, is well established (Randel and Wu 1999). Recent work has also highlighted seasonal Antarctic warming that may be related to changes in stratospheric circulation (Hu and Fu 2009; Lin et al. 2009). In the tropics, however, past research has until recently shown only small seasonal variation in temperature trends (Randel et al. 2009; Ramaswamy et al. 2001).

Increases in the strength of the stratospheric circulation are seen in middle-atmosphere model simulations forced by greenhouse gases (Butchart et al. 2006) and some models predict greater increases in boreal winter than in other seasons. This would be expected to cause seasonal differences in temperature trends in the tropical stratosphere (Butchart et al. 2006). Increases in the circulation with seasonal differences could also be produced by changes in ozone concentration (Li et al. 2008). On the other hand, Fu et al. (2010) report that the GCMs used for the Intergovernmental Panel on Climate Change Fourth Assessment Report (IPCC AR4) show little or no seasonal difference in tropical stratospheric temperature trends. It is therefore of interest to examine the seasonality of temperature trends in the tropical stratosphere and their relation to trends near the poles.

Thompson and Solomon (2005) showed trends for 1979–2003 at 70 mb in the tropics varying seasonally by at least 0.5 K decade^{-1} but characterized the winter cooling maximum as "weak." Randel et al. (2009) showed a weaker seasonal variation of trends in satellite data for the stratosphere for 1979–2007 for 30°N–30°S and identified a "weak maximum in cooling trends during July–November," in contrast to the winter maximum found for radiosonde data in Thompson and Solomon (2005). Recently, Fu et al. (2010) used the seasonal cycle in the dynamically forced component of lower stratospheric trends from the Microwave Sensing Unit (MSU) satellite for the tropics, Arctic, and Antarctic as evidence of

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TABLE 1. Datasets used.

Dataset	Acronym	Stations*	Reference
Radiosonde Atmospheric Temperature Products for Assessing Climate	RATPAC	11	Free et al. (2005)
Hadley Center Atmospheric Temperatures	HadAT2	27	Thorne et al. (2005)
Iterative Universal Kriging	IUK	43	Sherwood et al. (2008)
Radiosonde Observation Correction using Reanalysis 1.4	RaobCORE	>100	Haimberger (2007)
Radiosonde Innovation Composite Homogenization	RICH	>100	Haimberger (2007)
RATPAC-Lite	R-Lite	2	Randel and Wu (2006)
MSU–Remote Sensing Systems 3.2	RSS		Mears and Wentz (2009)
MSU–University of Alabama Huntsville 5.2	UAH		Christy et al. (2003)

* For radiosonde datasets, number of stations between 10°N and 10°S.

changes in the stratospheric circulation. The present work uses several radiosonde datasets to examine the seasonal trend pattern in the tropical stratosphere, revealing its vertical and horizontal extent, and, by using data before 1979, tests its robustness with respect to time period and its relation to trends in the Arctic stratosphere.

2. Data and methods

Table 1 lists and describes the radiosonde and satellite datasets used in this paper. All radiosonde datasets used include adjustments, described in the references listed in Table 1, to reduce temporal inhomogeneities caused by changes in instruments or procedures. The HadAT2 data are derived from the 5° zonal means on the Hadley Centre Web site. RaobCORE and RICH gridded data were averaged over 10° latitude bands. For IUK and RATPAC, station data have been averaged by latitude band without gridding. I constructed RATPAC Lite using RATPAC station data for the stations identified in Randel and Wu (2006). Datasets not already in anomaly form were converted to anomalies by subtracting the mean annual cycle from the monthly mean temperatures.

Only IUK makes homogeneity adjustments separately by season. For the other radiosonde datasets, the adjustment process does not account for possible seasonal variations in biases. Except for IUK, which ends in 2005, all datasets include data through the end of 2009.

I computed least squares linear trends by 10° latitude band and pressure level for each month separately and also computed trends using the nonparametric median of pairwise slopes method. I got MSU-equivalent temperatures for each radiosonde dataset by applying a weighting function appropriate to land to the 10° zonal mean temperature data. Uncertainty of the trends was determined from the standard error of the trends, taking into account the autocorrelation of the time series. To assess the stability of the trends to choice of time period I also computed trends for each of the 33 twenty-year time periods from 1958–77 to 1990–2009.

3. Results

All radiosonde datasets show the expected cooling in the stratosphere and warming in the troposphere in the deep tropics (10°N–10°S) to at least some extent (Fig. 1), but month-by-month analysis of trends gives a striking seasonal variation in temperature trends for 1979–2009. The cooling trend is at least 1 K decade^{-1} at 50 mb for December–January for all radiosonde datasets except HadAT2 but is at a minimum in March or April (earlier at 30 mb and later at 70 mb). The increased cooling seems to begin at 30 mb in July and moves downward over August–December. The seasonal pattern is reversed in the troposphere, with a maximum warming for October–February and a minimum in June, most visible at 300 mb, but the seasonality of the trend is much weaker at this altitude than at 50 mb. In between, at 100 mb, the seasonality is minimal. The datasets differ strongly as to the size of the warming trend in the upper troposphere, as shown also in Santer et al. (2008), but agree well on its seasonal variation.

Examination of trends by month at 50 mb for zonal means from pole to pole (Fig. 2) shows that the latitudinal extent of this seasonal trend pattern varies among the datasets. Also visible are the more intense spring cooling trends in the Arctic and Antarctic that coincide with the times of maximum ozone loss, although the lack of coverage near the South Pole causes most datasets to give an incomplete view there. The tropical cooling trend maximum coincides with a warming trend in December and January in the Arctic, but the Arctic warming is not statistically significant. These basic features look similar in all six radiosonde datasets and are also shown in Thompson and Solomon (2005) using 70-mb radiosonde data for 1979–2003. The seasonal differences in the tropics are less visible in the analysis of Randel et al. (2009) using MSU satellite data. Secondary cooling maxima are apparent in the tropics in October in several of the datasets. This cooling could be related to dynamic warming in late winter in the Antarctic (Fu et al. 2010).

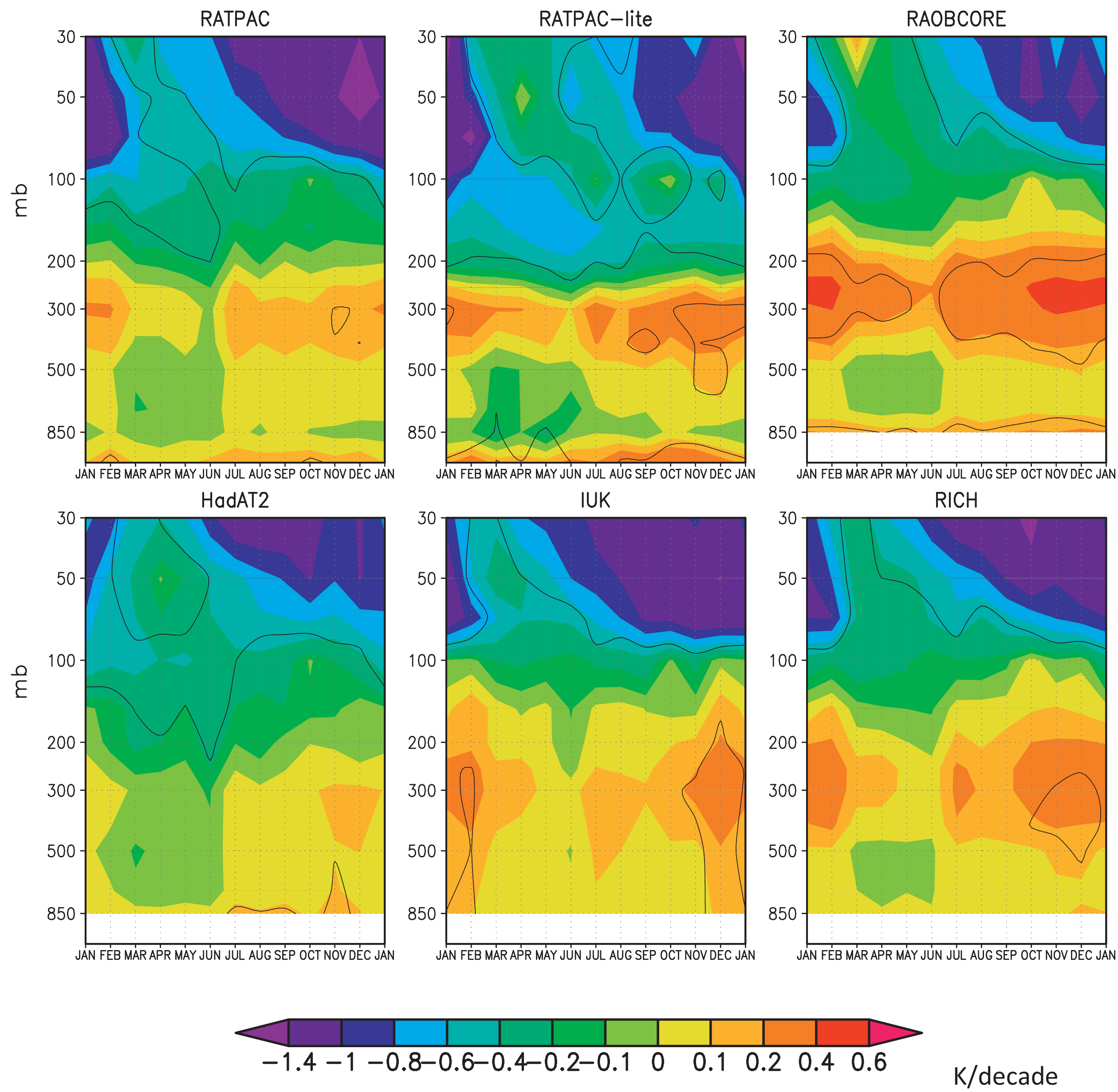

FIG. 1. Trends (K decade^{-1}) in radiosonde temperature data from six datasets, averaged for 10°N–10°S for 1979–2009 (2005 for IUK), calculated for individual months. Black lines enclose the areas where trends are significant at the 95% confidence level.

Comparing trends from all radiosonde datasets for 10°N–10°S at 50 mb on one plot (Fig. 3a) shows that the seasonal trend pattern is similar for all, although RATPAC Lite is much noisier than the others. Results are similar using the median of pairwise slopes instead of least squares trends. Trends for 1979–2005 (not shown) are more negative for all months than those for 1979–2009, and this may explain most of the difference between results for IUK, which ends in 2005, and those for RAOBCORE and RICH. The majority of datasets show the maximum cooling trend in December and the minimum in March, so the trend in the March minus December temperature time series gives a measure of the seasonal variation in trend. The trend in this difference for 1979–2009 is ~1 K decade^{-1} and is statistically significant for all radiosonde datasets but HadAT2. A similar cycle exists in the MSU lower stratospheric data for the deep tropics (Fig. 3b) but the amplitude is reduced, as expected since the satellite data for the stratosphere include information from levels that have a less pronounced seasonal trend pattern. The trend in the time series of the difference between December and March temperatures

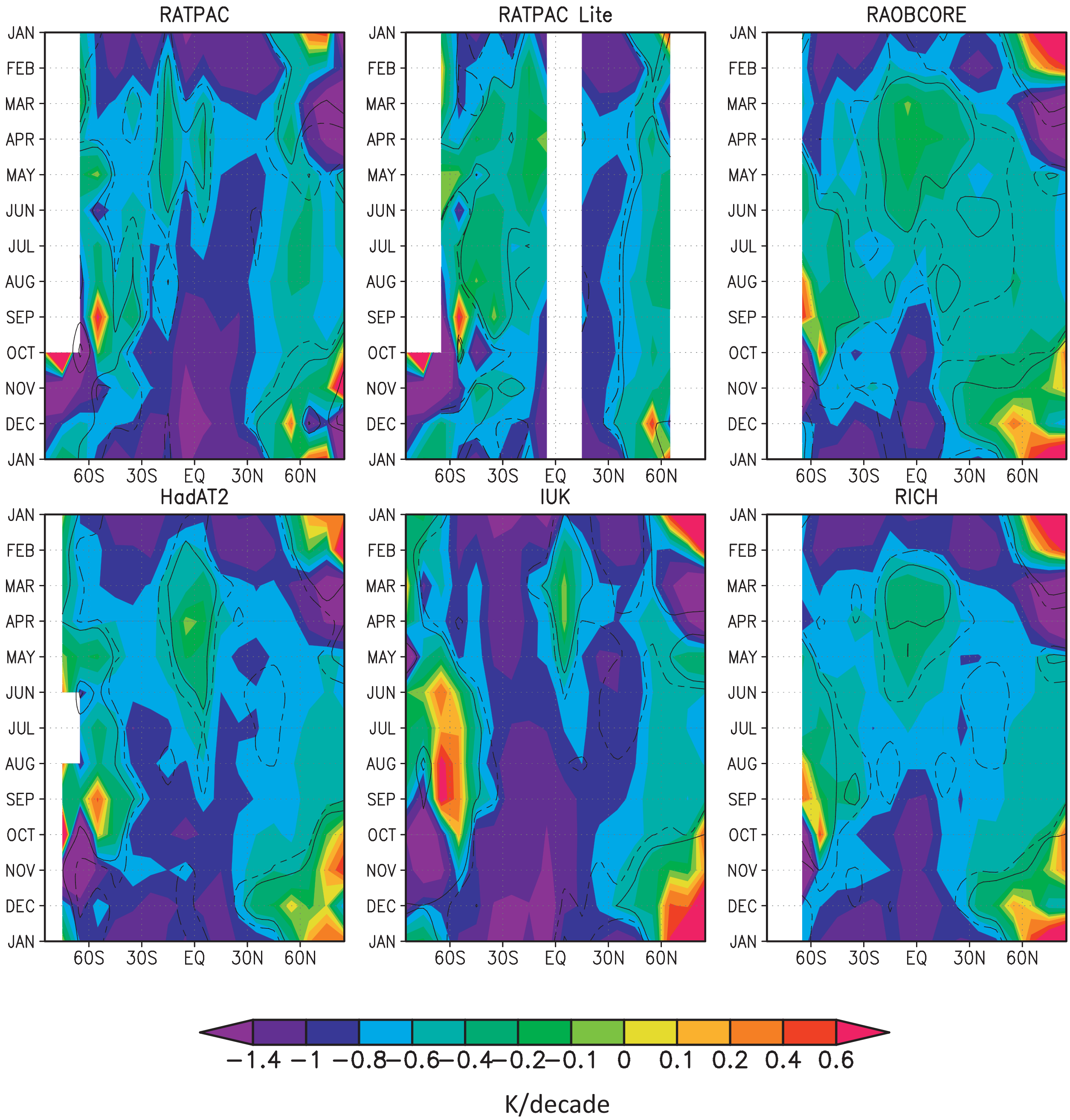

FIG. 2. Trends for 1979–2009 (except for IUK, which is 1979–2005) at 50 mb for 10° zonal mean radiosonde temperatures, calculated for individual months, in K decade^{-1}. Solid black lines enclose the areas where trends are significant at the 95% confidence level; dashed lines indicate areas with 99% significance.

for the MSU data in this region is −0.42 ± 0.28 for UAH and −0.37 ± 0.26 for RSS. The seasonality of MSU-equivalent trends from the radiosonde datasets is quite similar to that from the MSU data, with the exception of those from RATPAC-Lite. Differences between the MSU and radiosonde trends are typically largest during January–April and smallest for July–September.

Are these patterns robust to the choice of time period? Figure 4a shows trends in radiosonde temperature anomalies for December minus those for the following March for selected 20-yr time periods in the deep tropics. The difference is negative for all 20-yr time periods ending in 1995 and later, but not for 20-yr periods ending in the late 1980s or earlier for most datasets. Time series

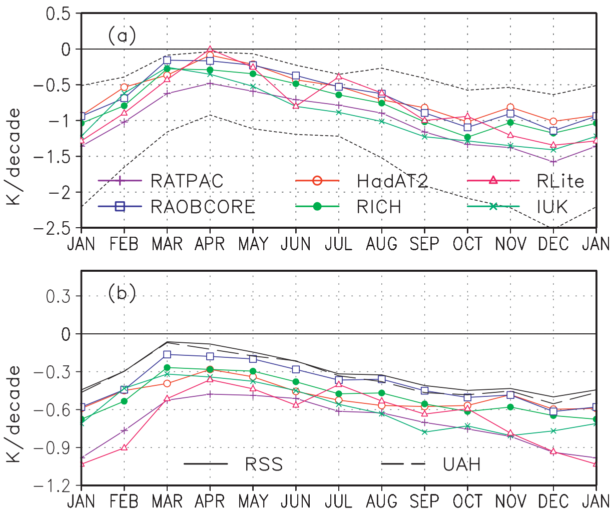

FIG. 3. (a) Trend for 1979–2009 (K decade^{-1}) at 50 mb, averaged for 10°N–10°S, calculated by month. Dotted lines represent the limits of the 95% confidence interval for RATPAC. (b) Trends in RSS and UAH MSU lower stratosphere temperature and equivalent temperatures calculated from radiosonde datasets, for 1979–2009, for 10°N–10°S, by month.

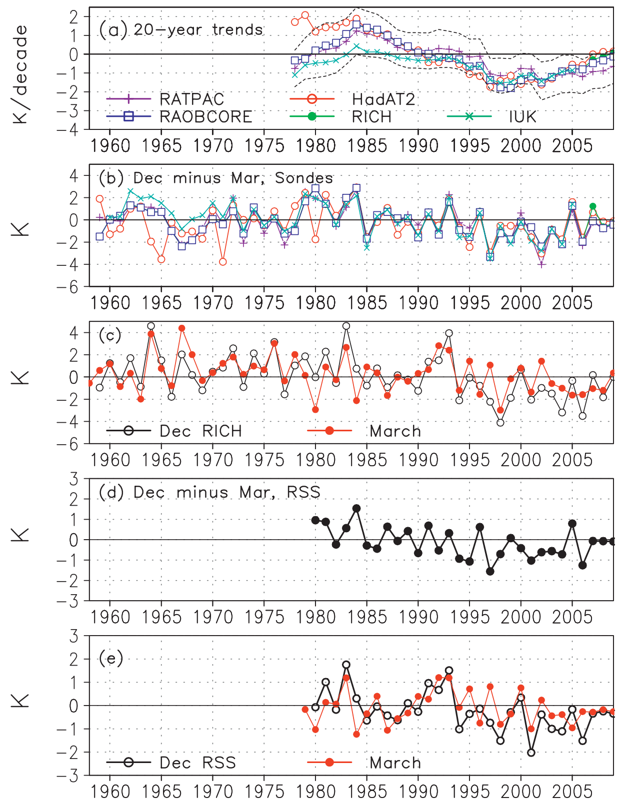

FIG. 4. (a) Temperature trend for December minus trend for the following March at 50 mb in the deep tropics, for sliding 20-yr time periods, plotted by the last year of the time period. Dotted lines denote the 95% confidence interval of the RATPAC trends. (b) Time series of difference between temperature anomalies for December and those for March at 50 mb for 10°N–10°S for five radiosonde datasets. (c) Temperature anomalies in RICH radiosonde data at 50 mb between 10°N and 10°S, for December and March. (d) Temperature for December minus temperature for March for MSU lower stratosphere temperature between 10°N and 10°S using RSS data. (e) As in Fig. 4c, but for RSS lower stratospheric temperatures. For all panels, data are plotted according to the year in which March occurs.

of the difference between temperature anomalies in December and those for the following March for radiosonde datasets (Fig. 4b) show a relative cooling trend from around 1980 through the late 1990s, but this trend is not evident before the early 1980s. Figures 4a and 4b also suggest that the difference between trends in December and March has decreased in the last 5 years, with the trends for 1990–2009 roughly the same in both months. However, a similar plot of 15-yr trends (not shown) is relatively flat and negative for the last few years, suggesting that the behavior of the 20-yr trend curve since 2005 may be related to temperatures earlier in the record rather than to changes in the last few years. In many of the radiosonde datasets, the trend difference at 50 mb seems to arise in large part from a difference in the size of the downward shift in temperature in the mid-1990s, with December anomalies decreasing more than those in March. Figure 4c shows an example using RICH data (note that Fig. 4c also suggests the possibility that the warming effect of the volcanic eruptions is greater for December than for March, which could contribute to the apparent seasonal pattern in trends). This pattern is visible but weaker in the MSU satellite data (Figs. 4d,e).

For 1979–2009, the Arctic and tropical seasonal radiosonde trend patterns show an inverse relationship (see Fig. 5a herein; Fu et al. 2010), with Arctic warming coinciding with tropical cooling in the winter and the reverse in spring, although the winter trends vary strongly between datasets. However, time series of winter Arctic stratospheric temperatures show large interannual variability (Fig. 6b), and no long-term trend is visually apparent. The time series of December minus March temperature anomalies for the Arctic (Fig. 6a) shows a maximum temperature difference in 1997, corresponding to a minimum for the tropics at the same time, as seen in Fig. 4b. More generally, the seasonal differences for the Arctic and tropical stratospheres seem to vary inversely on the interannual time scale. However, the high point in the tropical difference series in the early 1980s is much less visible for the Arctic.

Trends for 1960–2009 (Fig. 5b) show a somewhat different and weaker seasonal pattern from those for 1979–2009, with weak warming in the Arctic in February and none in January or December. Tropical trends for that time period do not correspond as closely to Arctic trends

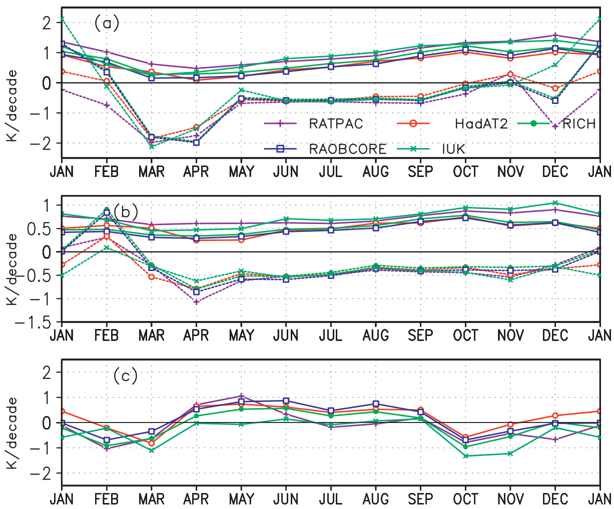

FIG. 5. (a) Trends for 1979–2009 at 50 mb from 10°N to 10°S (solid lines), multiplied by −1 for comparison, and from 70° to 90°N (dotted lines). (b) As in Fig. 5a, but for 1960–2009. (c) Trends for 1995–2009 for 10°N–10°S in radiosonde data.

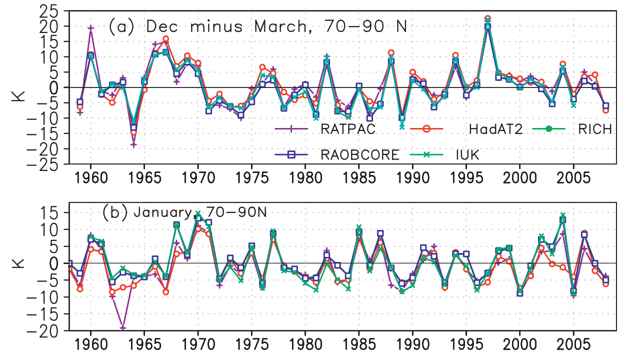

FIG. 6. (a) Time series of difference between temperature anomalies for December and those for March at 50 mb for 70°–90°N for five radiosonde datasets. (b) Time series of temperature anomalies at 50 mb from 70° to 90°N for January for five radiosonde datasets.

as they do for 1979–2009. Although the annual trend for 1995–2009 in the tropics is near zero for most datasets, monthly trends (Fig. 5c) show a distinct seasonal pattern that is different from that for 1979–2009, with cooling maxima of up to 1 K decade^{-1} in February and October (rather than December–January) and warming in April–September.

4. Discussion

There is reason to believe that the size of the annual mean stratospheric cooling in the tropics may be exaggerated in radiosonde datasets (Randel et al. 2009), but less reason to be suspicious of the seasonal trend cycle. If measurement errors were dependent on the ambient temperature, they could be significantly different in different seasons. However, Sherwood et al. (2008) found no systematic seasonal difference in the homogeneity adjustments required outside of the Northern Hemisphere extratropics. The seasonal pattern of trends is consistent among sets with different adjustment approaches, including one that adjusts the seasons separately, and is similar to that in the MSU data, suggesting that it is real. Nevertheless, this pattern seems to have arisen only recently, which may explain why it has not received much attention in earlier work. The lack of a strong seasonal pattern for trends ending before the mid-1990s in the radiosonde data suggests that the change might represent a temporary shift related to interannual or decadal-scale variability rather than a long-term trend. However, it is possible for a long-term trend to combine with short-term natural variability to create the appearance of a sudden change, as with the apparently steplike changes in global mean stratospheric temperatures in the early 1980s and 1990s (Ramaswamy et al. 2006; Thompson and Solomon 2009). The seasonal trend pattern could reflect changes in stratospheric ozone, which declined after 1980 and reached a minimum in the mid-1990s, somewhat like the December–March temperature differences shown in Fig. 4b.

The tropical lower stratosphere is cooler in boreal winter than in summer, with a minimum around December and a maximum in July and August (Yulaeva et al. 1994) and peak-to-trough amplitude of 8 K around 70 mb (4–5 K at 50 mb). The peak cooling trend for 1979–2009 at 50 mb thus coincides with the climatological temperature minimum, but the minimum cooling trend occurs earlier in the year than the climatological temperature maximum. The ~1 K decade^{-1} peak-to-trough amplitude of the seasonal difference in trends is therefore up to 20% of the total climatological seasonal cycle—not a small change!—and has the effect of amplifying the cycle and shifting its phase. If these changes represent long-term shifts rather than decadal-scale variability, accounting for this seasonal pattern in the trends could be an interesting test for models.

The seasonal cycle in the tropical stratosphere is generally attributed to the greater strength of the Brewer–Dobson circulation in boreal winter, with the resulting upwelling producing cooler temperatures at that time (Yulaeva et al. 1994). Thompson and Solomon (2009) show evidence that the overall cooling trend in the tropical stratosphere is related in part to increases in tropical upwelling associated with changes in the Brewer–Dobson circulation. Model studies suggest such an increase is a likely result of greenhouse gas increases and may be greater in boreal winter (Butchart et al. 2006). Fu et al. (2010) present evidence that the warming trend in the Arctic winter coupled with the greater cooling in the tropical stratosphere in that season is also related to changes in the Brewer–Dobson circulation. However, Engel et al. (2009) show evidence that the age of stratospheric air has not changed beyond measurement uncertainty in the past 30 years, which does not support claims of an overall increase in the strength of the stratospheric circulation.

The work presented in the present paper confirms the apparent inverse relationship of Arctic and tropical stratospheric trends for 1979–2008 shown in Fu et al. (2010). Other work has shown a strong inverse relationship between tropical stratospheric temperatures and those in the extratropics on monthly (Yulaeva et al. 1994) and interannual time scales (Ueyama and Wallace 2010), and the time series of seasonal temperature differences in the tropics and Arctic shown in Figs. 4b and 6a suggest a similar relationship. However, because of the large interannual variability in the Arctic winter stratosphere, seasonal trend patterns in that region seem less robust than those in the tropics (Labitzke and Kunze 2005). Data for the last 15 years and for the presatellite period also suggest that the seasonal differences in trend in the tropics may not be consistent over time.

5. Conclusions

Cooling trends for 1979–2009 vary strongly with season in the tropical stratosphere, with the largest cooling in December and the least cooling in March and April. This pattern is strongest near the equator at 50 mb, where a cooling of at least 1 K decade^{-1} occurs in January. The difference of up to 1 K decade^{-1} between trends in December and those in March is statistically significant in most datasets. The greater cooling in boreal winter disappears below 100 mb, and the troposphere has an opposite and smaller pattern.

Understanding these seasonal differences in trends might help to explain the cooling trends in this region. The winter maximum in cooling in the tropics, combined with a recent warming trend in the Arctic stratosphere in January, may reflect an increase in the strength of the stratospheric circulation. However, the strong seasonal pattern of trends in the tropical stratosphere for 1979–2009 seems to come from a seasonal difference in the size of the stratospheric cooling beginning in the mid-1990s, is less apparent in trends from earlier time periods, and differs from the pattern in trends since 1995. Winter trends in the Arctic are also dependent on time period and are not statistically significant, so it is unclear whether the apparent relation between Arctic and tropical trend seasonality is robust. Comparisons with results from models with adequate representation of the stratosphere could help to determine whether the observed changes in seasonality of tropical temperature are related to greenhouse gas, ozone, or other forcings.

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