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Radiosonde Daytime Biases and Late–20th Century Warming

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The temperature difference between adjacent 0000 and 1200 UTC weather balloon (radiosonde) reports shows a pervasive tendency toward cooler daytime compared to nighttime observations since the 1970s, especially at tropical stations. Several characteristics of this trend indicate that it is an artifact of systematic reductions over time in the uncorrected error due to daytime solar heating of the instrument, and should be absent from accurate climate records. Although other problems may exist, this effect alone is of sufficient magnitude to reconcile radiosonde tropospheric temperature trends and surface trends during the late 20th century.

Atmospheric models and simple thermodynamic arguments indicate that tropospheric and surface temperature changes should be closely linked (*1*). Radiosonde data during the late 20th century, however (*2*–*5*) have not shown warming commensurate with that reported for the surface (*1*, *6*, *7*). The main discrepancy is in the Tropics during the last two decades of the 20th century.

A number of design changes to radiosonde systems over the years may have affected trends (*8*). In fact, the spread of trends among stations significantly exceeds that implied by satellite data (*9*), suggesting that trends in the observation bias typically exceed those of the actual temperature at individual stations.

Among the most serious known problems is bias due to solar heating of the temperature sensor (*10*). For many radiosonde designs this can elevate the temperature several °C above ambient during daylight, an effect that must be removed via an estimated correction. For other designs no correction is standard even though the effect may not be completely absent. Adjustment of climate records for instrument changes using their documented histories is problematic (*8*, *11*).

One can try to remove undocumented artifacts by careful examination of the data itself. Several such efforts have detected hundreds or thousands of apparent artifacts (*3*–*5*, *12*). Their net effect on trends was found to be large only in the stratosphere. Revised trends were still lower than those indicated by the Microwave Sounding Unit (MSU) in both the troposphere and stratosphere (*13*). Since empirical separation of artificial discontinuities from genuine variability is extremely challenging in correlated time series (*14*, *15*), especially as changes can probably occur in many small steps (*16*), it is not clear how successful the above efforts may have been in detecting discontinuities—or avoiding false adjustments—of amplitudes well below 1°C.

Here we adopt a strategy for quantifying trend errors that does not require identifying specific change events. The strategy applies only to the solar heating error and does not detect other errors. It relies on the fact that the diurnal temperature range in the free troposphere, hence its expected trend, is small and possesses known characteristics that differ from those expected from a radiation error.

The diurnal temperature variation in Earth's atmosphere is a tide arising from its direct solar heating and from diurnal variations of convective heating driven by the diurnal variation of surface temperature. Atmospheric heating, which occurs primarily in the stratosphere via ozone absorption, drives migrating resonant oscillations that cause temperature fluctuations of several °C in the upper stratosphere. In the troposphere, weaker solar heating occurs due mainly to near-infrared absorption by water with a contribution from dark aerosols. These influences produce diurnal temperature fluctuations of 1°C or less in the free troposphere (*17*). Near the land surface, variations of 5-15°C occur due to surface diurnal heating (*18*); over oceans, variations are of order 1°C.

Because atmospheric tides are a linear phenomenon (*19*), the diurnal variation of temperature is proportional to that of the heating, though the two need not be in phase. Trends of ~ –0.2°C decade^{-1} are evident in the land surface diurnal temperature range (DTR) (*20*) which amount to roughly 2% of the mean DTR per decade. Tropospheric water vapor and stratospheric ozone changes do not exceed a few percent per decade in recent decades (*21*, *22*), and absorption increases weakly with concentration due to line saturation (*23*). It follows that tides could not have changed by more than a few percent, or ~ 0.01-0.02°C/decade. Because of this, trends in the observed day minus night difference in radiosonde temperatures should provide a sensitive detector of changes in the daytime observation bias.

We examine the diurnal range using the CARDS dataset with no adjustments (*24*). We calculated a quantity ΔT equal to the difference between adjacent 0000 UTC and 1200 UTC sonde flights, wherever such pairs were available. Pairs were used regardless of which time of day came first, but ΔT was always defined as 0000 minus 1200. At all CARDS stations with sufficient data, we fitted linear trends to ΔT for the same periods (1959-1997 and 1979-1997) documented by Lanzante *et al.* (LKS) (*3*). LKS considered temperature trends at 87 stations denoted here as the "LKS subset."

Figure 1 shows the 1979-97 trend in stratospheric ΔT at Tropical stations plotted by longitude, together with a sinusoid representing the local time of day at 0000. These data clearly show that the trend is in phase with solar heating, with daytime readings growing cooler compared to nighttime, and is pervasive.

Although clearest in the stratosphere, these characteristics appear also at tropospheric levels. In fact, tropospheric and stratospheric ΔT trends are highly correlated in general: for example, $r = 0.85$ between 50 and 300 hPa over 1959-97. This is not true for natural temperature variability, which tends to be anti-correlated below and above the tropopause in both low and high latitudes (*26*), nor is it true of the tide itself. According to wind data, tidal fluctuations in the troposphere should lag those at 50 hPa by about six hours (*27*); this is also simulated by the NCAR CAM3 (not shown), and appears (albeit with slightly less shift) in carefully selected radiosonde temperature data (*17*). Consequently we expect peak ΔT magnitudes near 90E and 90W. However, prior to the 1980's ΔT peaked broadly around 0 and 180 where solar heating was greatest. Only by the late 1990's did the pattern in the troposphere begin to appear as expected.

To quantify the anomalous signal we defined an additional quantity $\Delta T'$, equal to $\pm\Delta T$ with sign determined by longitude to make it daytime (6 am to 6 pm) minus nighttime. To minimize sunrise-time ambiguities we did not compute $\Delta T'$ at stations within 10° of the 90E/W meridians.

A map of the trend in upper tropospheric $\Delta T'$ (Fig. 2) reveals regional variations. The largest trends occurred the Tropics, particularly among Indian, African, and island stations where transitional problems have been reported previously (*3*, *4*, *28*). Trends were small in North America and most of Asia. We see no evidence in Figure 2 that the ΔT trends at stations in the LKS subset differed systematically from those at neighboring, non-LKS stations. However, the most affected stations tend to be in sparsely sampled areas where they would be strongly weighted in any spatially representative climatology. We omitted all Indian stations from subsequent analysis, because these show anomalously large ΔT and have other problems (*3*, *4*).

Following LKS we averaged $\Delta T'$ over three belts: the Tropics, the northern hemisphere extratropics (NH), and southern hemisphere extratropics (SH). Since tropospheric temperature is expected to lag insolation by about six hours, the zonal means $\langle\Delta T'\rangle$ should be small due to near cancellation of different longitudes.

The time series of tropical upper tropospheric $\langle\Delta T'\rangle$ (Fig. 3), however, shows significant long-term variations. Daytime temperatures warmed prior to about 1971, reaching values near 0.5°C above nighttime, then began a slow cooling trend. By the mid- to late 1990's, $\langle\Delta T'\rangle$ finally dropped to a level commensurate with predictions. The trend was particularly strong during the satellite era beginning in 1979. Since 1997 the trend has leveled off.

The linear trend in $\langle\Delta T'\rangle$ is shown by altitude in Figure 4 for the two LKS time periods, for all three belts. It increases rapidly in the stratosphere, is weak in NH but strong in the other two belts, and is much stronger during the 1979-97 period than the longer period starting in 1959.

This trend appears unrealistic in several respects. First, it is almost two orders of magnitude larger than can be justified physically based on the known forcings (a run of the CAM3 GCM with half-normal ozone, an unrealistically large change, caused tropospheric ΔT to change by only 13%). In fact, if a 0.5°C change in diurnal temperature range were caused by a change in daytime heating from *any* source, then the radiative relaxation time scale of ~ 1 month for deep perturbations (*29*) would imply a change in equilibrium temperature of 10-20°C. Clearly nothing like this has happened. Moreover, the spatial patterns of this trend are inconsistent with absorbing aerosol (which decreases with height and is scanty in SH) or convective heating (absent in the stratosphere) as a cause. Finally, the strong correlation of the ΔT trend between the troposphere and stratosphere is unnatural.

We are left to propose that the trends are caused by decreases over time in the uncorrected heating of the sensor. This is plausible *a priori* given the history of radiosonde development and improvement efforts, and is fully consistent with all characteristics of the trend here documented: strong in the stratosphere (due mainly to the low thermal diffusivity of thin air) and in phase with solar heating. The smaller effect in NH is consistent with the expected superior stability of those stations.

The trend reported from a particular set of stations can be adjusted to a nighttime-only value by adding an adjustment δ_{sol} equal to the trend in $\langle\Delta T'\rangle$ multiplied by a factor f representing the fraction of the reported trend coming from daytime data (*25*). This assumes that stations that do not collect nighttime data are just as susceptible to spurious daytime trends, on average, as those that do.

MSU (Microwave Sounding Unit) Channel 2 data can be used to test this assumption. We require only trend differences between sites, which are much more robust to analysis method than the overall MSU trend itself. We use diurnal-mean MSU trends from the University of Alabama at Huntsville at LKS station locations (*3*). Our assumption implies that daytime-only stations will cool more compared to colocated MSU retrievals than will twice-daily stations. The calculated differences, given in Table 1 (we combine SH and NH here since there are no daytime-only LKS stations in NH), are fully consistent with this, particularly for the Tropical stations. In the extratropics there are only four daytime-only stations so the MSU test is less meaningful, but the two independent estimates do agree within 0.03°C/decade.

To illustrate the importance of the heating bias, we have computed its impact δ_{sol} on the trends at LKS stations. The LKS *f* factors, unhomogenized trends ("UNADJ"), and trends adjusted only for solar heating are given for the middle troposphere and lower stratosphere in Table 2. In the stratosphere, our δ_{sol} is similar to the total adjustments by LKS and others, with trends moving closer to those from MSU (*13*). At the tropical tropopause (of relevance to stratospheric water vapor), δ_{sol} is somewhat smaller than LKS's. In the troposphere, however, δ_{sol} is much larger than previous adjustments. In fact, the tropical trend with this adjustment (0.14°C/decade over 1979-97) would be consistent with model simulations driven by observed surface warming, which was not true previously (*1*). One independent indication that the solar-adjusted trends should be more accurate is their consistency across latitude belts: for the period 1979-97, the spread of values fell by 70% in the lower stratosphere and 25% in the troposphere.

Though this is encouraging, our confidence in these nighttime trends is still limited given that other radiosonde errors have not been addressed. 1958-97 SH trends seem unrealistically high in the troposphere, especially with the δ_{sol} adjustment, although this belt has by far the worst sampling. Previous homogenization efforts typically produced small changes to mean tropospheric trends, which could mean other error trends cancel out δ_{sol} in the troposphere. In our judgment, however, such fortuitous cancellation of independent errors is unlikely compared to the possibility that most solar artifacts were previously either missed or their removal negated by other, inaccurate adjustments. To be detected easily a shift must be large and abrupt, but δ_{sol} was spread out over so many stations (79% of stations during 1979-97 and 90% during 1959-97 experienced ΔT trends significant at 95% level), at such modest levels, and of sufficient frequency at many stations that many may have been undetectable. Most important of all, jumps in the difference between daytime and nighttime monthly means would be detectable at only a few tropical stations since most lack sufficient nighttime data. In any case, we conclude that carefully extracted diurnal temperature variations can be a valuable troubleshooting diagnostic for climate records, and that the uncertainty in late-20th century radiosonde trends is large enough to accommodate the reported surface warming.

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Fig. 1. Trend in 50 hPa ΔT (0000 UTC T minus 1200 UTC T) during 1979-97 vs. longitude at all Tropical stations. Sine wave (not a curve fit) represents the negative of solar forcing of ΔT, peaking where 0000 UTC falls at midnight and troughing where it falls at noon. Error bars are 1-σ sampling uncertainties.

Fig. 2. Trends in 300 hPa day-night difference $\Delta T'$ during 1979-97, in K/decade. LKS station subset is indicated by large squares. One station (Mumbai) is off scale, not shown. Solid symbols are significant at 95% confidence; thick open symbols do not pass the test at 300 hPa but are significant in the stratosphere (50 hPa).

Fig. 3. Monthly mean 300 hPa $\langle \Delta T' \rangle$, the average day-night temperature difference, at the 10 LKS tropical stations spanning the 1959-97 period.

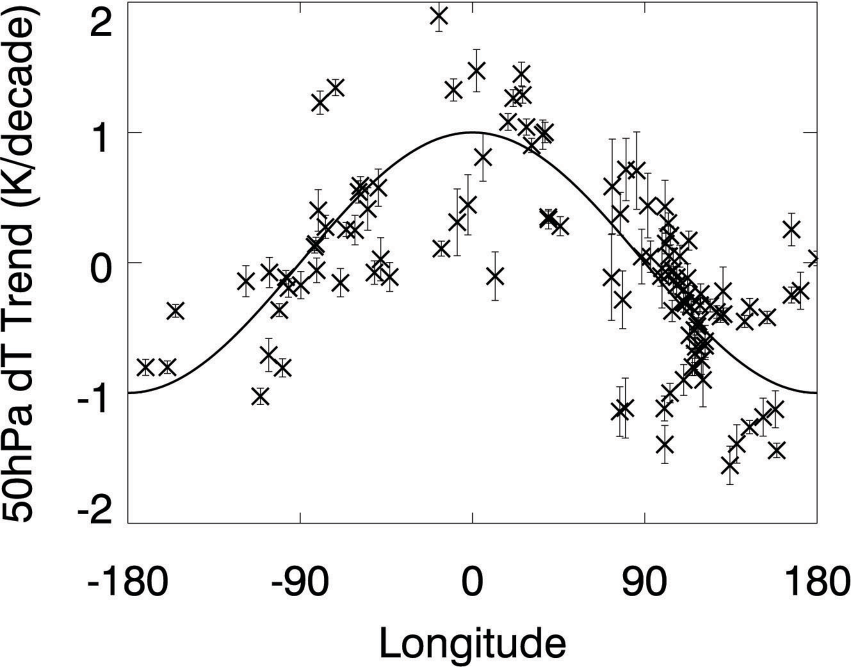
Fig. 4. Trend in $\langle \Delta T' \rangle$ during 1979-1997 (top) and 1959-1997 (bottom) at LKS stations. Green = Tropics (30N-30S), red = SH (90S-30S), blue = NH (30N-90N). Error bars are one-sigma sampling uncertainty. Figures in parentheses are the number of stations used.

Table 1. Mean difference in ΔT trend 1979-97, vertically weighted according to the MSU channel 2 profile, sonde minus MSU (first two columns) among LKS stations; the differences of this quantity between the two station types (third column); and prediction of the latter based on assumptions in text (last column). All quantities in °C/decade. Figures in parentheses are the number of stations used (*25*).

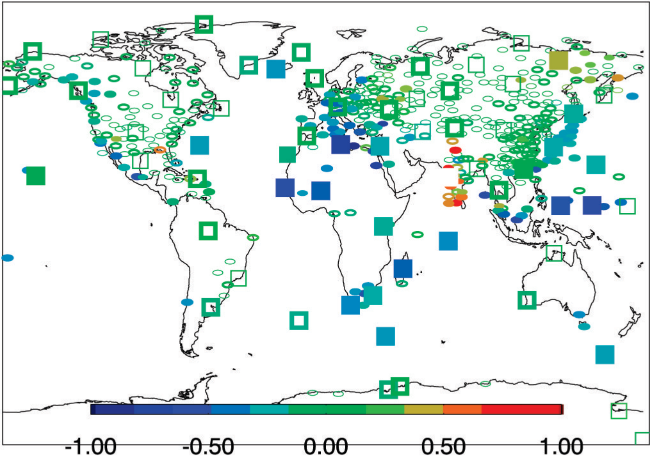
	Daytime only	Twice-daily	Difference	Predicted Difference
Tropics	–0.228 (17)	–0.102 (8)	0.130	0.120 (18)
Extratropics	–0.052 (4)	–0.029 (43)	0.023	0.050 (38)

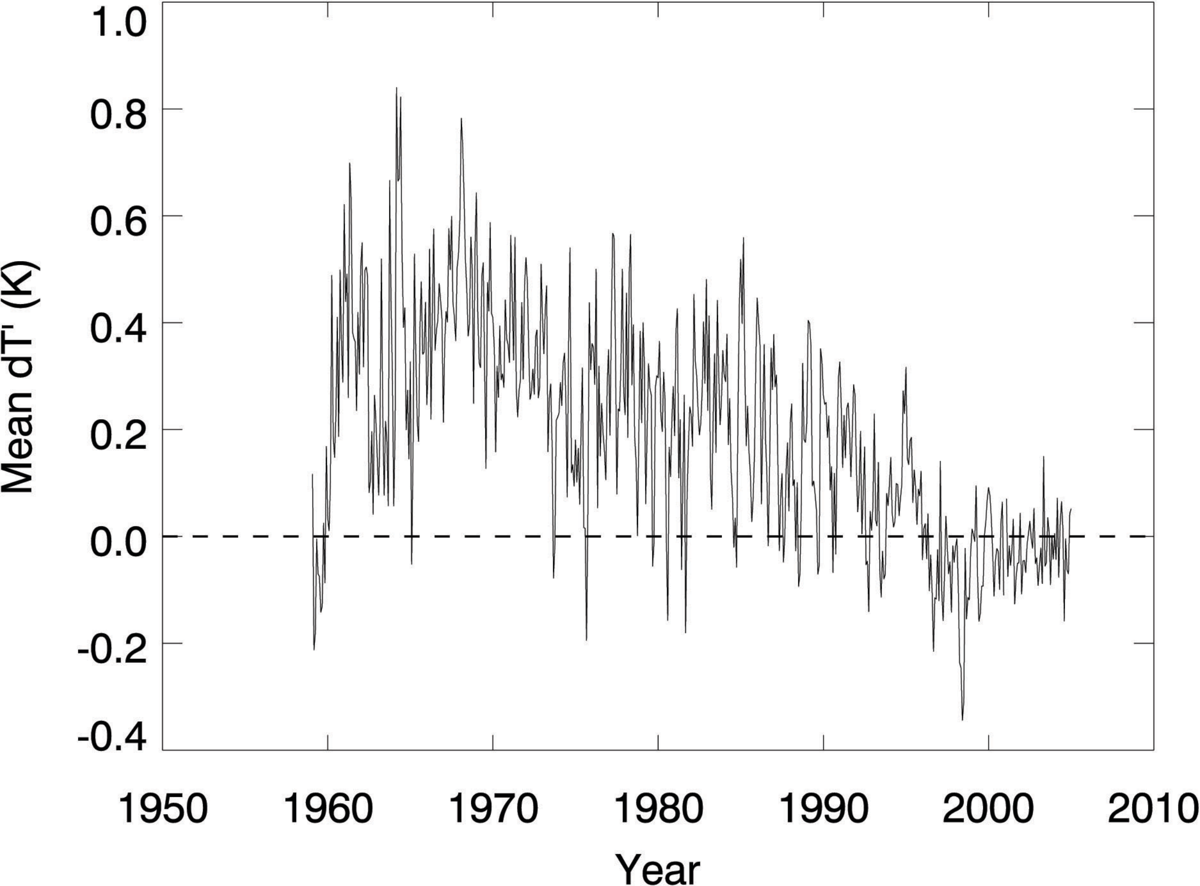
Table 2. Layer-average tropospheric and stratospheric temperature trends (in K/decade) reported by LKS for unhomogenized data ("orig"), and with solar heating bias removed ("new"). Factor f is specific to LKS station subset. Uncertainties are 1-σ sampling uncertainty in the solar heating bias correction only.

1979-97	Tropics	NH extratropics	SH extratropics
f	0.84	0.50	0.67
50-100 hPa (orig)	–1.30	–0.85	–1.04
50-100 hPa (new)	–0.81 ± 0.08	–0.78 ± 0.03	–0.67 ± 0.08
850-300 hPa (orig)	–0.02	+0.10	–0.07
850-300 hPa (new)	+0.14 ± 0.04	+0.14 ± 0.02	+0.01 ± 0.04
1959-97	Tropics	NH extratropics	SH extratropics
50-100 hPa (orig)	–0.71	–0.43	–0.50
50-100 hPa (new)	–0.52 ± 0.06	–0.38 ± 0.02	–0.30 ± 0.07
850-300 hPa (orig)	+0.17	+0.06	+0.25
850-300 hPa (new)	+0.23 ± 0.03	+0.07 ± 0.01	+0.30 ± 0.03

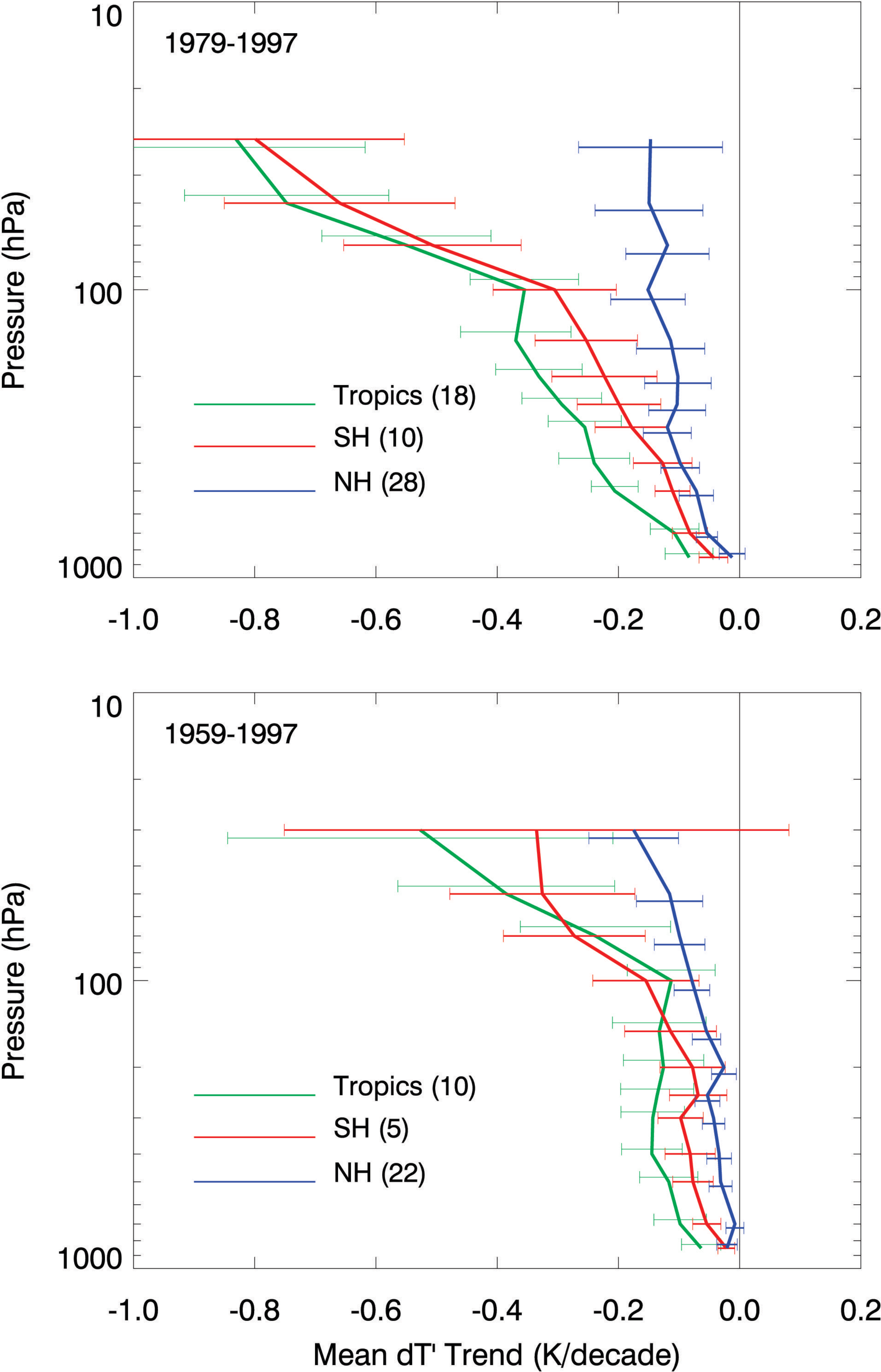


50hPa dT Trend (K/decade)
2
1
0
-1
-2
-180
-90
0
90
180
Longitude


-1.00
-0.50
0.00
0.50
1.00



1.0
0.8
0.6
0.4
0.2
0.0
-0.2
-0.4
Mean dT' (K)
1950
1960
1970
1980
1990
2000
2010
Year


1979-1997
Tropics (18)
SH (10)
NH (28)
1959-1997
Tropics (10)
SH (5)
NH (22)
Pressure (hPa)
10
100
1000
-1.0
-0.8
-0.6
-0.4
-0.2
0.0
0.2
Mean dT' Trend (K/decade)