GEOPHYSICAL RESEARCH LETTERS, VOL. 25, NO.17, PAGES 3371-3374, SEPTEMBER 1, 1998

Middle atmosphere cooling trend in historical rocketsonde data

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Abstract. Data from the historical rocketsonde network demonstrate that significant cooling of the upper stratosphere and lower mesosphere (~30–60 km) occurred in northern midlatitudes of the western hemisphere and in the tropics during 1962–1991. The downward trend of temperature averaged over this layer was about -1.7 K/decade and temperatures were apparently modulated by the solar cycle with amplitude ~1.1 K. The trend was a function of height and somewhat larger in the lower mesosphere relative to the middle and upper stratosphere.

Introduction

Cooling of the middle atmosphere is expected in response to the increasing concentration of greenhouse gases of anthropogenic origin. This signature is the largest and theoretically the most obvious component of climate change. Detection of a temperature trend above 10 hPa, however, is compromised by a number of problems including poor spatial and temporal coverage, instrument calibration, and inhomogeneities within each dataset. Nevertheless, there is general agreement that significant cooling has occurred over the last 2–3 decades. The observational evidence includes measurements from the Stratospheric Sounding Unit (SSU) [*Nash and Edge*, 1989], the historical rocketsonde network [*Angell*, 1987, 1991; *Golitsyn et al.*, 1996, and references therein], and Rayleigh lidar [*Hauchecorne et al.*, 1991; *Keckhut et al.*, 1995]. There is also indirect evidence of cooling in sodium lidar data suggesting a hydrostatic contraction of the atmosphere below ~95 km [*Clemesha et al.*, 1992], and a possible increase of noctilucent cloud sightings in the summer mesosphere [*Thomas*, 1991].

Identification of a climate trend distinct from natural interdecadal variability will require much more data than are currently available. Nevertheless, it is likely that observations in the modern era (1950s and thereafter) will play a pivotal role in the detection of human influence, having been acquired in a time period when such an effect might be first observable. Data from the historical rocketsonde network provide the longest continuous evidence of cooling in the upper stratosphere and lower mesosphere (~1962–1991). In order to make optimum use of these data it has been necessary for us to assemble the dataset from various sources and to carefully analyze the data for possible biases and inhomogeneities.

Paper number 98GL02385.
0094-8534/98/98GL-02385$05.00

Data Analysis

Data from the historical rocketsonde network (World Data Center 'A') including North American stations and a few tropical sites for the period 1969–1991 were obtained from the National Center for Atmosphere Research, supplemented by additional data from the Climate Prediction Center (Mel Gelman, personal communication) and National Climatic Data Center. These data are comprised of individual rocket soundings accompanied by rawinsonde data from the same stations. For the period before 1969 we obtained pre-processed data formerly utilized by scientists of the meteorology group at Control Data Corporation (David Venne, personal communication). These data were originally acquired from rocket soundings but had been processed

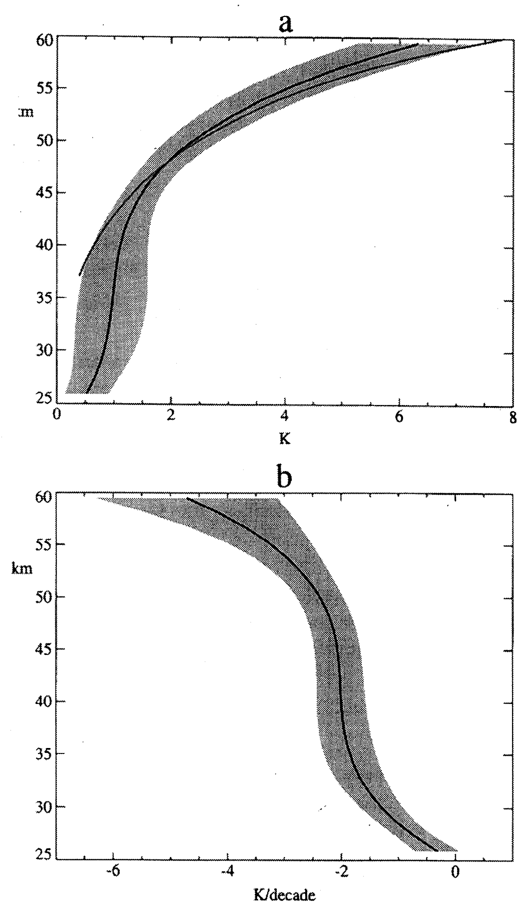

Figure 1. (a) Average of empirical temperature correction profiles (black line) plus or minus one standard deviation (shading). The standard correction is also shown (gray line). (b) Average profile of temperature trend, after the average correction was applied to stations individually, plus or minus one standard deviation (shading).

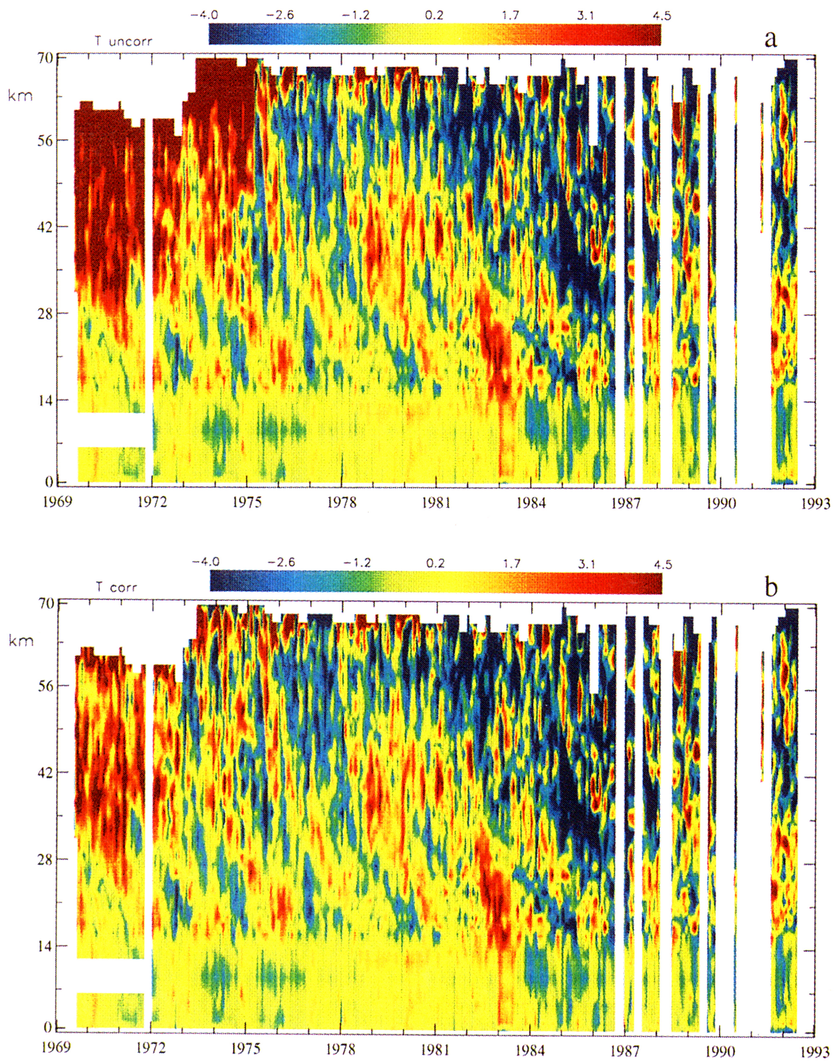

Figure 2. Time-height cross section of monthly mean deseasonalized temperature at Kwajalein. (a) Uncorrected and (b) corrected data are shown with the same color scale. At Kwajalein, the transition to corrected data occurred in April 1975. Units: K.

onto a regular vertical grid at 2 km intervals. The preprocessed data were obtained by us through 1982, and were found to agree with the original data in their period of overlap. Of the 22 stations included in this rocketsonde network, 17 provide data for more than 10 years and 9 provide data for more than 20 years. Data at most stations were analyzed but in this letter we focus attention on six of these lying either in western hemisphere midlatitudes or tropics:

Ascension (14.8°W, 8.6°S),
Kwajalein (167.4°E, 8.4°N),
Barking Sands (159.9°W, 22.0°N),
Cape Kennedy (80.7°W, 28.3°N),
Point Mugu (119.5°W, 34.1°N),
and
Wallops Island (75.7°W, 37.5°N).

Their location outside the winter polar vortex is such that interannual variability is relatively small.

Angell [1987, 1991] compared rawinsonde and rocketsonde temperatures at 26–35 km and concluded that, because of a sharp apparent cooling of rockets with respect to rawinsondes in the early 1970s, the rocket trend at that time was spurious. This is consistent with a suggestion by *Johnson and Gelman* [1985], who examined data from the North American network in the band 25–55°N. Our analysis shows that individual stations did not exhibit this cooling at the same time, and the spurious 'trend' really amounts to a near-discontinuity in measured temperature. We examined header information for soundings at tropical and midlatitude stations and determined that the spurious jump was due primarily to a change from uncorrected to corrected temperatures (to account for aerodynamic heating, etc.) rather than an instrumental change (e.g., Arcasonde to Datasonde). In this letter we therefore display temperature data using all instrument types. Included in the dataset are a few measurements obtained from falling spheres. The sphere data are colder, generally falling outside the range of observed layer-mean temperatures, but are relatively few in number and do not affect the results significantly.

In order to utilize uncorrected data before the early 1970s it is necessary to subtract a positive temperature correction profile. The standard correction is documented in *Krumins and Lyons* [1972]. For comparison, we chose instead to derive empirical correction profiles for each station in the following manner. Biennial-mean deseasonalized temperature profiles were obtained immediately before and after the switch from uncorrected to corrected data at each station (the biennial interval chosen to minimize effects of the quasi-biennial oscillation). We then assumed that the two biennial-mean profiles should have been equal apart from a linear trend. The empirical correction profile and final trend estimate were obtained at each level by iterating this procedure a few times until convergence. The average correction profile is shown in Figure 1a, and agrees well with the standard correction, except at lower levels where the empirical correction is about 1 K. Both corrections increase with altitude near the stratopause in approximately exponential fashion; the scale height is about 7.9 km for the standard correction, close to a density scale height. For the purpose of plotting data above 60 km, where our derivation of empirical correction would be unreliable, the correction profile was extrapolated using a constant scale height.

Application of the average correction to uncorrected data reduces the net trend over the entire record but does not eliminate either the trend or an apparent solar cycle influence as demonstrated below. The average trend of the six stations as a function of height is shown in Figure 1b: approximately -2 K/decade in the upper stratosphere, increasing to in excess of -4 K/decade in the lower mesosphere.

Results

Monthly mean uncorrected and corrected temperatures at Kwajalein are shown in Figures 2a and 2b, respectively. These figures display rawinsonde data below 3.7 scale heights (~25 hPa), rocketsonde data above 4.7 scale heights (~9 hPa), and a linear blend of the two in their region of overlap. Prominent features include descending phases of the quasi-biennial oscillation, an apparent decadal variation coinciding with the solar cycle (with maximum temperature near solar maximum and vice versa), and a cooling trend throughout the record. Note the apparent positive correlation with the solar cycle: e.g., solar maxima occurred around 1969, 1981, and 1990; solar minima occurred around 1976 and 1986. A transient effect of the El Chichón eruption in 1982 was prominent at Kwajalein in the middle half of this year with warming in the lower stratosphere and cooling aloft as documented by *Dunkerton and Delisi* [1991]. A cooling trend was present at most levels of the middle atmosphere, whereas the apparent solar influence was seen primarily above 35 km.

Figure 3a compares rawinsonde and corrected rocketsonde temperatures averaged vertically in their region of overlap, at five stations. At each location the two datasets agree reasonably well, especially the high-frequency variability; however, there was a brief period near 1970–71 when rocket temperatures were anomalously high by about 2 K, and another interval after 1984 when rockets were slightly cool by about 1–2 K. These discrepancies affect the trend estimates, which range from -0.19 to -0.73 K/decade for rawinsondes, and from -0.81 to -1.33 K/decade for rocketsondes. The downward trend is real, but possibly exaggerated in rocketsonde data. At higher levels, there is good agree-

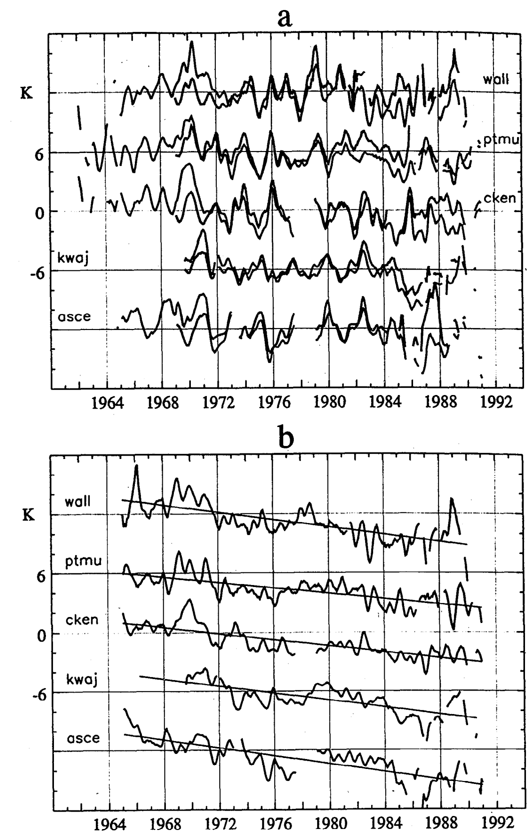

Figure 3. (a) Layer-mean temperature at 3.7-4.7 scale heights for five stations, derived from corrected rocketsonde data (black line) and rawinsonde data (gray line). (b) Layer-mean rocketsonde temperature at 4.1-7.9 scale heights. A linear least-squares fit to each series is also shown (light solid).

ment between stations concerning both the downward trend and apparent solar influence, as shown in Figure 3b. Here, temperatures are averaged vertically over the layer 4.1–7.9 scale heights (approximately 28–56 km). Over the last 25 years, downward trends of magnitude -1.38 to -2.01 K/decade are obtained after correction. Amplitude of the decadal oscillation is ~1.1 K.

Figure 4 shows the average of the individual station data shown in Figure 3b. Data are plotted only when three or more stations have data in a given month. The dashed straight line is the linear least-squares fit through two solar cycles, starting at the solar minimum in 1965 and ending at the solar minimum in 1986. The slope of this line is -1.76 K/decade. The solid straight line is the linear least-squares fit through two solar cycles, starting at the solar maximum in 1969 and ending at the solar maximum in 1990. The slope of this line is -1.69 K/decade. The 10.7 cm solar flux is shown in the bottom part of this figure. Several interesting features are notable. For example, the data show a positive correlation with the solar flux, indicating an apparent solar cycle in the height-averaged temperature data. It should be recognized that the apparent solar signal is small and is best seen when the data are averaged vertically and data from several stations are blended together; the significance of this result should not be overstated. The data also show a reasonably constant trend over nearly three decades (in the sense that similar trends are obtained using subintervals within this

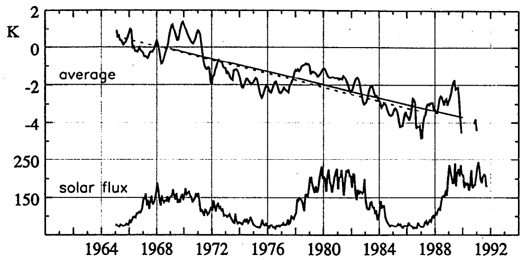

Figure 4. Average of layer-mean temperatures at 4.1-7.9 scale heights for the five stations of Figure 3. Trendlines between solar maxima (solid) and solar minima (dashed) are superposed.

record stretching over two solar cycles). This result appears to validate the temperature correction method even though the break points occurred at different times depending on location. For comparison, using only one solar cycle [e.g., *OTP*, 1988], the trends for solar minimum to solar minimum are -2.53 and -1.92 K/decade, and the trends for solar maximum to solar maximum are -1.93 and -1.28 K/decade.

Conclusion

Data from the historical rocketsonde network demonstrate that significant cooling of the upper stratosphere and lower mesosphere (~30–60 km) occurred in northern midlatitudes of the western hemisphere and in the tropics during 1962–1991. The downward trend of temperature data averaged over this layer was about -1.7 K/decade and temperatures were apparently modulated by the solar cycle with amplitude ~1.1 K. The trend was a function of height and somewhat larger in the lower mesosphere relative to the middle and upper stratosphere.

Uncorrected temperature data prior to the early 1970s require the user to correct for aerodynamic heating and other heat transfer effects; the date before which correction is required varies from station to station. Correction profiles derived empirically are similar to the standard correction, increasing with altitude approximately in exponential fashion with a scale height close to that of atmospheric density. The magnitude of derived temperature trend depends on the application of a suitable correction to early data; this is the most salient issue for trend studies using these data. The overall behavior of temperature time series does not depend significantly on thermistor type (e.g., Arcasonde or Datasonde) since instrumental changes were relatively few and most variability was observed in periods of time monitored by the same instrument. Other factors not discussed here such as measurement time of day and agreement with adjacent rawinsonde might alter the trend estimate, but our investigation (to be reported separately) indicates that these are relatively minor effects.

Putting our results in a larger context, although evidence of similar cooling has been found in other datasets [e.g., *Golitsyn et al.*, 1996], it is likely that temperature trends associated with climate change are not globally or hemispherically uniform but contain a dynamical component associated with planetary waves and induced mean meridional circulation. Further analysis of existing ground-based and satellite datasets and synthesis with newer methods of observation (e.g., lidar) will help to clarify the nature of the climate change signal as affected by atmospheric dynamics.

Acknowledgments. This research was supported by the National Aeronautics and Space Administration, Contract NASW-97010, and by the National Oceanic and Atmospheric Administration, Grant NA76GP0354.

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(Received April 22, 1998; revised July 9, 1998; accepted July 15, 1998.)