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Article

Satellite Global and Hemispheric Lower Tropospheric Temperature Annual Temperature Cycle

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Abstract: Previous analyses of the Earth's annual cycle and its trends have utilized surface temperature data sets. Here we introduce a new analysis of the global and hemispheric annual cycle using a satellite remote sensing derived data set during the period 1979–2009, as determined from the lower tropospheric (LT) channel of the MSU satellite. While the surface annual cycle is tied directly to the heating and cooling of the land areas, the tropospheric annual cycle involves additionally the gain or loss of heat between the surface and atmosphere. The peak in the global tropospheric temperature in the 30 year period occurs on 10 July and the minimum on 9 February in response to the larger land mass in the Northern Hemisphere. The actual dates of the hemispheric maxima and minima are a complex function of many variables which can change from year to year thereby altering these dates.

Here we examine the time of occurrence of the global and hemispheric maxima and minima lower tropospheric temperatures, the values of the annual maxima and minima, and the slopes and significance of the changes in these metrics. The statistically significant trends are all relatively small. The values of the global annual maximum and minimum showed a small, but significant trend. Northern and Southern Hemisphere maxima and minima show a slight trend toward occurring later in the year. Most recent analyses of trends in the global annual cycle using observed surface data have indicated a trend toward earlier maxima and minima.

Keywords: global and hemispheric annual temperature cycles; global and hemispheric annual maximum and minimum temperatures

1. Introduction

While most of the focus on climate change has been on multi-decadal global warming [1], changes in the annual cycle of the global and hemispheric lower tropospheric temperature have received some attention. Limited studies analyzing surface data have shown mixed results; Stine *et al.* [2] and Mann and Park [3], for example, state that there has been a 1.7 day shift to earlier seasons between 1954 and 2007, although they report that none of the IPCC models reproduce this shift. Thomson [4], in an analysis of a specific regional data set (Central England), found a shift to later seasons. White *et al.* [5] find no systematic earlier shift in the spring leaf-out of vegetation in North America. The dates of the global maxima and minima are a complex function of many factors [2] such as atmospheric circulation patterns, shifts in ocean patterns, changes in cloud cover and land surface, *etc.*, as well as changes in the Earth's energy budget. Any continual, robust systematic change in the annual cycle should be investigated to see if they can be linked to the factors above.

Stine *et al.* [2] in a comprehensive analysis of the surface annual cycle found that models during the latter half of the 20th century (which include the time period for the present satellite data set herein) have considerable variation in trend and for the mean of the models essentially no trend. In fact they concluded that failure of the models to replicate the observed trends in the annual cycle to earlier maxima suggest that the answer involves something that models do not capture. Based on sensitivity studies using a simple energy budget model they found that changes in greenhouse gases had little effect on seasonal timing in contrast to Thompson's analysis [4]. They did suggest based on the energy budget model that changes in land surface properties such as surface albedo, soil moisture, or insolation might contribute to the observed trend. Mann and Park [3] noted that 'scenarios [or factors affecting the trends in timing of the annual cycle] are difficult to resolve owing to the limitations of the observational data and potential shortcomings of certain climate processes'. Because of the concerns with global model adequacies expressed by [2,3], we do not attempt here to determine which of the many possible causes may be responsible for statistically significant trends or to compare the tropospheric trend in global maxima and minima here to specific model trends. Rather, we focus on presenting a new observed measure of the global annual cycle which is the annual cycle in the lower troposphere as observed by satellite.

Examining the dates and values of the global and hemispheric maxima and minima requires a robust temperature data set with true global coverage. Mann and Park [3] noted that lack of surface data at high latitudes where snow and ice changes might alter the annual cycle were not well observed in the surface temperature data set. The speculations of Stine *et al.* [2] that land surface changes might be responsible for the trends in seasonality in the observed data brings up the concern about whether the observed data in fact may be more sensitive to local land use change than models. We have chosen to use the LT (Lower Tropospheric) merged product of the MSU and AMSU (Microwave Sounding Unit and Advanced Microwave Sounding Unit, respectively) satellite radiometers which have provided global data since 1979 by the University of Alabama in Huntsville. The LT product is a weighted average of temperatures from the surface to about 10 km, but with the heaviest weighting below 5 km (e.g., see http://www.ssmi.com/msu/msu_data_description.html).

We believe that the LT temperature may be useful to determine a tropospheric global annual cycle as opposed to a surface annual cycle. The LT temperature has several features that make it desirable to calculate an annual cycle as a climate metric. First, it has global coverage. Second, it is not as affected by local land use change as in a surface data set. While the surface annual cycle is largely driven by the rate at which the surface gains and loses heat, the LT temperature includes the additional physics of how this heat is transferred into the deep atmosphere. The recent paper Christy *et al.* [6] provides a summary of observed trends in temperatures since 1979.

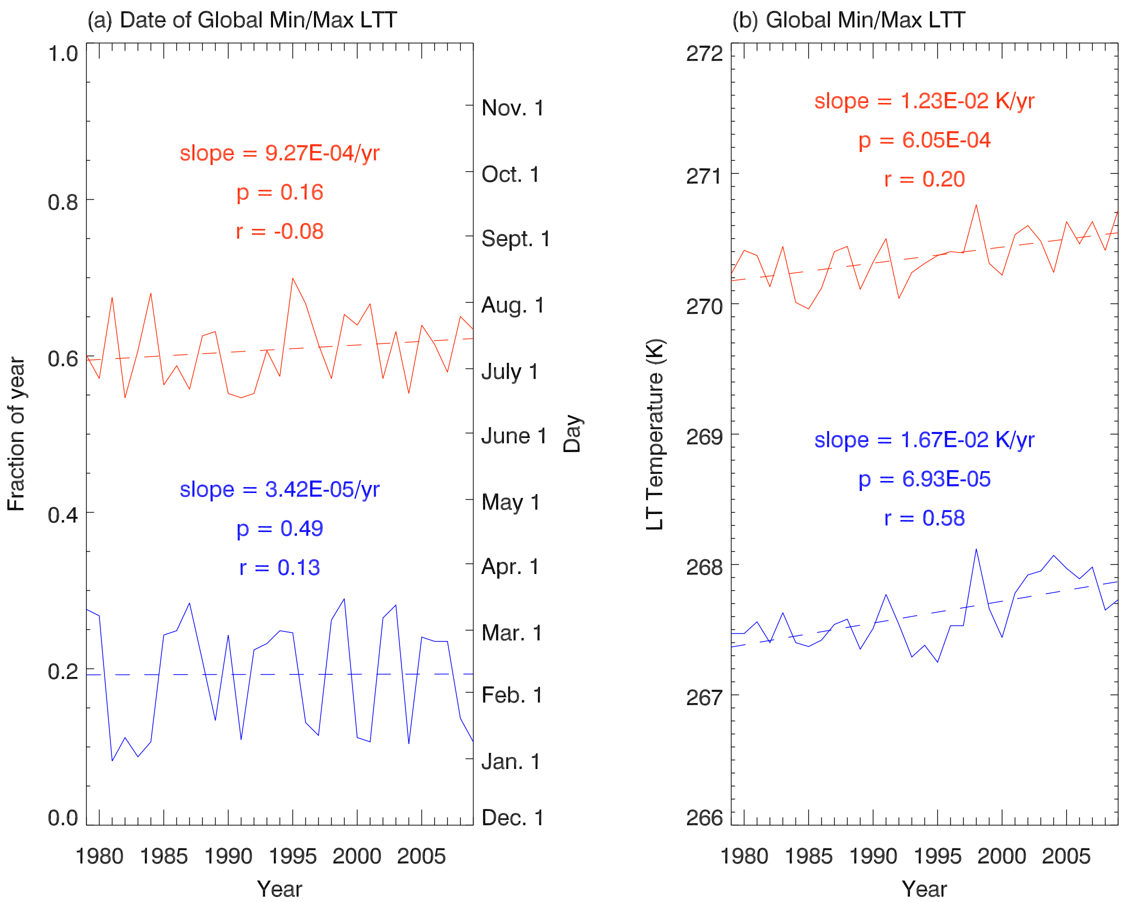
2. Observational Characteristics of the Lower Troposphere (LT) Satellite Product

The LT weighting profile provides a measure of the atmospheric temperature from the surface to about 10 km. The weighting profile itself is a function of the vertical temperature profile, as is the actual thickness of the weighted layer. The variation of the weighting function due to these effects is small however and has been studied rather extensively. Karl *et al.* [7] showed that a full radiation code or a static weighting function using vertical temperature profiles as produced with a model yielded radiances which were negligibly different. Christy and Norris [8] completed an analysis comparing outgoing radiances using a full radiation code using satellite temperature profiles for North American polar stations with radiances determined using the MSU weighting function, and the trends differed by less than 0.04 °C per decade. In an earlier study, Spencer and Christy [9] compared MSU temperatures as determined from a full radiation code with a static weighting function and found the difference was only 0.02 °C at the grid point level, well below the noise level of the typical satellite sensors. The influence of changes in the measured brightness temperatures due to changes in surface emissivity, due to soil moisture changes, ocean surface roughness, land vegetation changes, and cloud water have also been examined [10]. Emissivity changes over land, for example, were the least important and varied by only a small amount over the 20-year period examined resulting in no discernible impact on the diagnosed temperatures, even from variations in soil moisture. The only signals that had a detectable impact for anomalies and trends, and only locally, were about a 0.1 °C variation from transient wind changes at scattered parts of the ocean for annual averages. The variations of the parameters we are investigating here are at least a factor of 10 larger in magnitude. Thus we conclude that the MSU LT product is providing a reliable measurement of the vertically weighted LT temperatures from which the values of the annual maxima and minima may be determined. Moreover, calibration errors in the absolute accuracy of the lower tropospheric temperatures are not expected to cause errors in the annual cycle of the temperatures. We discuss the results of this study in the next section.

3. Analysis

Using daily averaged global LT temperature data provided by the University of Alabama in Huntsville, we extracted the maximum and minimum global mean temperatures as well as the dates that these occur globally and hemispherically for each year from 1979 to 2009, and straight line fits were found to the time series shown in the following figures. The significance of these regressions is tested by applying a one-tailed t-test using a t-score of slope divided by the standard error. A slope, positive or negative, was considered significant if the probability, p, of it having a t-score exceeding its observed value by chance (when it is in fact zero) is 5% or less (*i.e.*, a confidence of 95% or greater). These probabilities are given for each regression in Figures 1–3. Also shown in Figures 1–3 are the autocorrelation coefficients, r, with a one-year lag time which range from −0.19 to 0.58. Despite some of these large autocorrelations, all of the recalculated probabilities taking autocorrelation into account are essentially the same as without considering the autocorrelation, and thus are not shown here.

Figure 1. (a) Plot of the date of the maximum and minimum global MSU lower tropospheric temperature as indicated by the fraction of the year starting in December of the previous year (the actual dates are given for reference as well) for the period 1979 to 2009. The red lines are the maxima and the blue lines are the minima. The dashed lines are best fit straight lines to the data (see text, with the slopes given) which are insignificant at the 5% level (as indicated by the values of p). The autocorrelation coefficients (r) have a minimal effect on the values of p. **(b)** Values of the annual maxima and minima of the globally-averaged lower tropospheric temperatures. The maxima are in red, and the minima are in blue. The best fit straight lines are shown as the dashed lines which are significant at the 5% level (as indicated by the values of p). The autocorrelation coefficients (r) have a minimal effect on the values of p.



The dates of global LT temperature maximum and minimum for each year are shown as the solid red and blue lines in Figure 1(a). Note that the globally-averaged data indicates that the maxima usually occur in July (on 10 July on average) and the minima usually occur in January or February (on 9 February on average), but with a few occurrences in December and March. This indicates a dominance of the Northern Hemisphere for these global values due to the larger land mass in that hemisphere. The dashed lines are a straight line least squares fit to the data. They show a slight tendency for a later occurrence with time. However, the slopes for both lines are insignificant at the 5% level with p values of 0.16 and 0.49 for the maxima and minima respectively. Figure 1(b) shows the values of the maxima and minima globally-averaged temperatures for each year of the data set, while the dashed lines are best fits to the data as in Figure 1(a). Both lines appear to show a slight increase of a few tenths K over the 31-year period, and the slopes are significant with $p < 0.01$ for both.

Figure 2. Same as Figure 1(b) but for the **(a)** Northern and **(b)** Southern Hemisphere separately. All regressions are significant at the 5% level. The autocorrelation coefficients (r) have a minimal effect on the values of p.

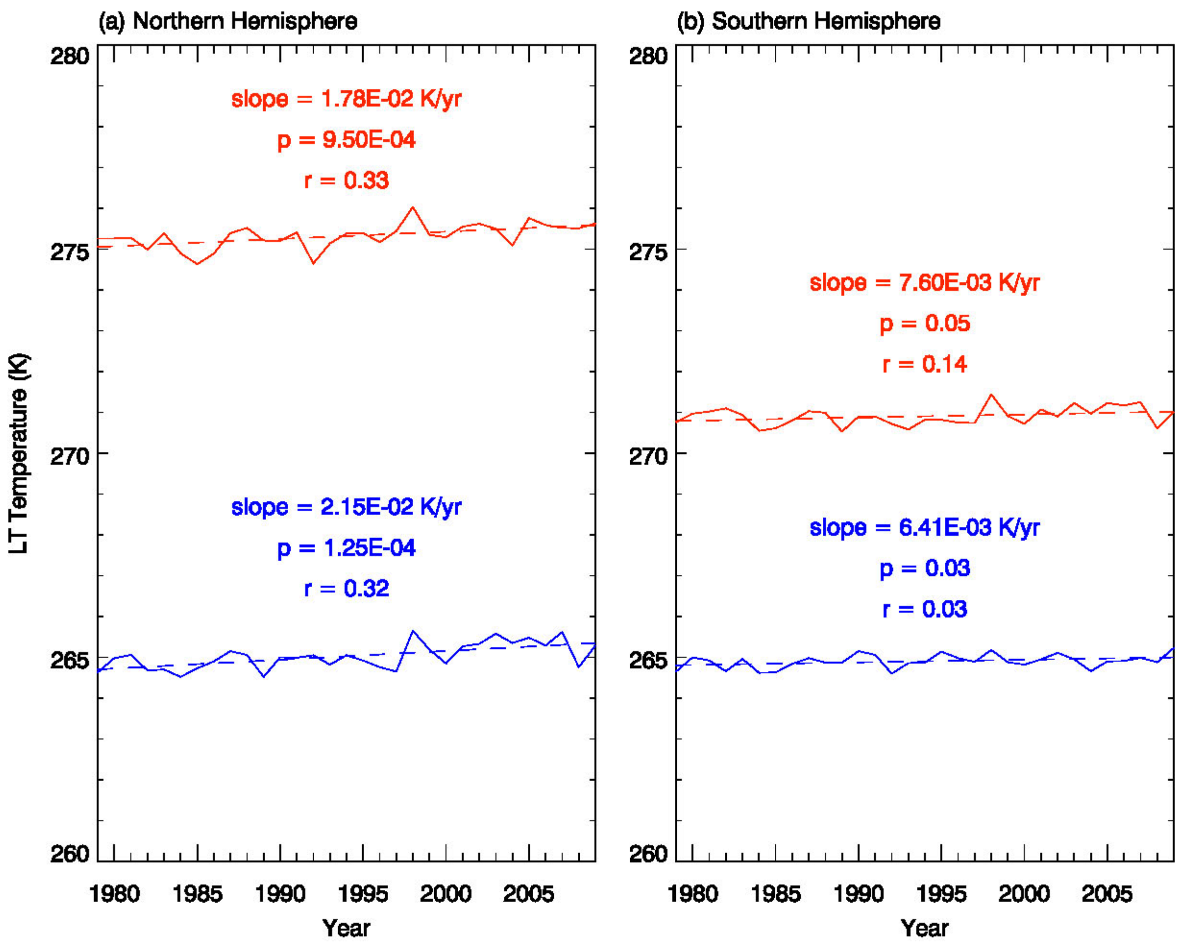


Figure 2 shows the yearly minimum and maximum temperatures recorded from 1979 to 2009 for the Northern and Southern Hemispheres respectively. The Northern Hemisphere shows a slight increase with time for both the maximum and minimum temperatures, as does the Southern

Hemisphere, but the latter trends are much smaller. Even so, the slopes of both the Northern and Southern Hemisphere annual maxima and minima temperatures were significant at the 5% level ($p < 0.01$ for the Northern Hemisphere and 0.05 and 0.03 for the Southern Hemisphere maximum and minimum respectively). The average date of maximum in the Northern Hemisphere is 21 July and for the Southern Hemisphere, 29 January. For comparison, Wallace and Osborn [11] had the observed surface maximum for the Northern Hemisphere on 24–25 July and for the Southern Hemisphere on 30–31 January.

Figure 3 shows that there were only very small trends in the time of the year that maximum and minimum temperatures were recorded for both hemispheres. All trends for these dates are very small and only the Southern Hemisphere minimum date is significant at the 5% level. The trends indicated a later occurrence for the Northern Hemisphere maxima as well as the Southern Hemispheric maxima and minima, while the Northern Hemisphere minima tended to occur slightly earlier.

Figure 3. Same as Figure 1(a) but for the **(a)** Northern and **(b)** Southern Hemisphere separately. Only the Southern Hemisphere minimum date regression is significant at the 5% level. The autocorrelation coefficients (r) have a minimal effect on the values of p.

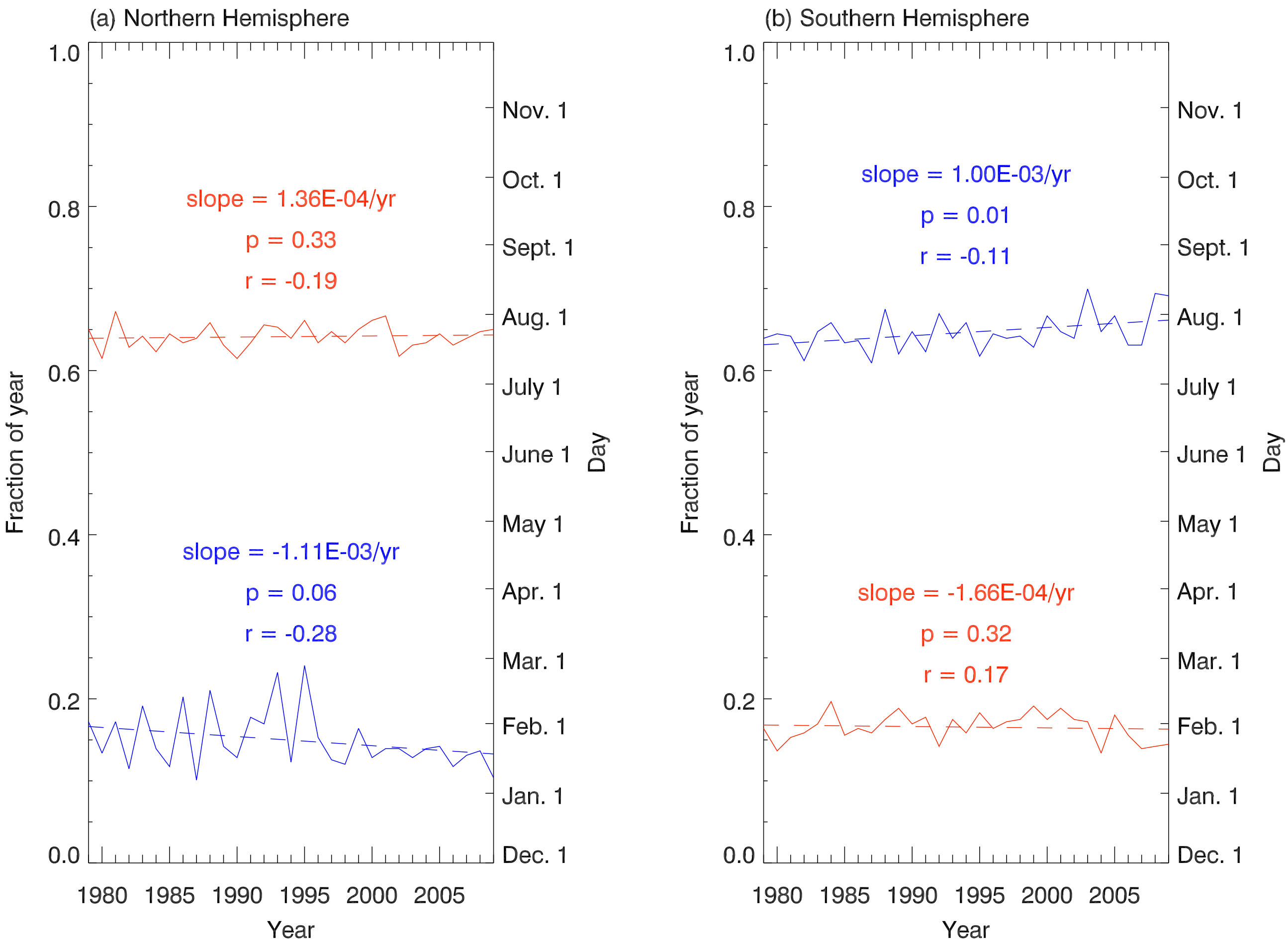
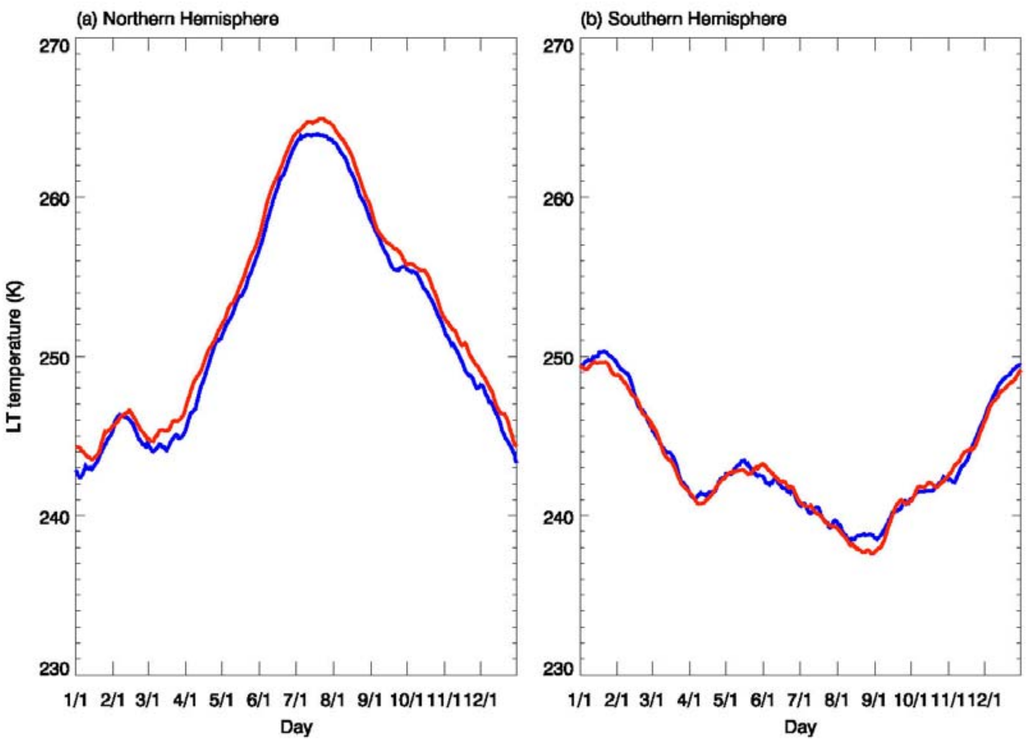


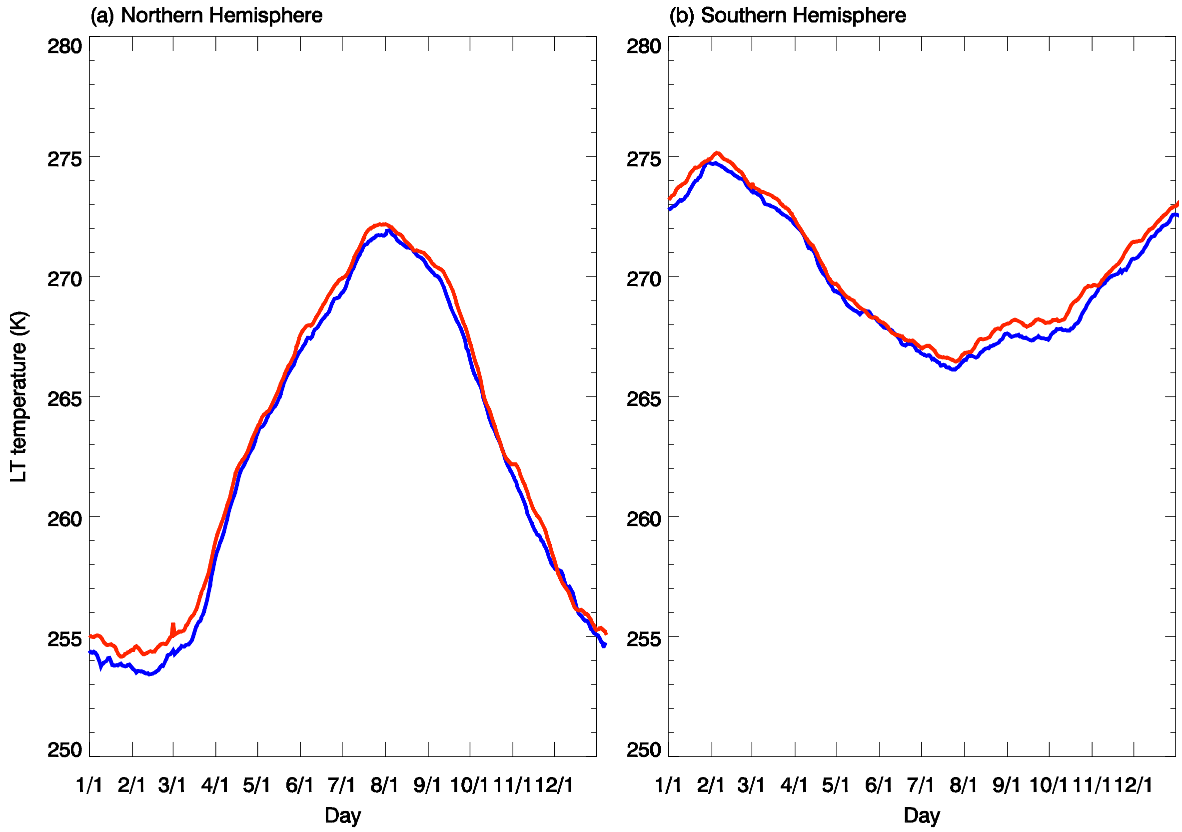
Figure 4 shows the average annual cycle of daily temperature for the 60° to 82.5° latitude belts for both hemispheres in two 10-year periods: 1980–1989 in blue and 2000–2009 in red. The strange “humps” apparent in both hemispheres in mid-winter in the Northern Hemisphere and fall (April, May, and June) in the Southern Hemisphere are likely due to the averaged effect of the sea surface emissivity. The LT product has about 20% of its signal coming from the surface, so the type of surface is important, particularly if it changes during the course of a year. Sea ice has a higher emissivity than water in the measured microwave band, so as water turns to ice in the fall, the total brightness temperature, which is what the MSU measures, increases due to the increase in surface emissivity even though the atmosphere is cooling. When the grid is totally frozen over, the continued gradual cooling of the atmosphere again dominates the average signal in these months. To check on the above hypothesis, we calculated the hemispheric trends from 32.5° to 50° only (Figure 5). If the "humps" are due to the freezing of the ice in polar latitudes, these trends should not be present in lower latitude plots, and indeed they are not there in the Northern Hemisphere. However, in the Southern Hemisphere, a smaller hump remains in August to October. We checked all latitude bands from 20°S to 57.5°S and a similar hump appeared in each band. At this time it is not clear to us what the cause is, and we will address this in our future work. However, this small effect does not materially alter the seasonal variations in the temperature analyses.

Figure 4. Average annual temperature cycles for Northern Hemisphere and Southern Hemisphere polar latitudes (60° to 82.5°) for an early period (1980–1989) and a later period (2000–2009). The blue line is for the early period and the red line is for the later period.



Since we are dealing with anomalies in MSU temperatures, this background freezing and thawing is fairly regular. The net impact of an actual loss in sea ice over time would result in a decrease in the MSU measured brightness temperature which would in turn cause an apparent net cooling in both hemispheres as measured by the MSU instrument. In the Northern Hemisphere (Figure 4(a)), it can be seen that the red curve is slightly above the blue curve for almost every month, representing a warming of the later period compared to the earlier one. For the Southern Hemisphere, Figure 4(b) indicates slightly colder winter and summer temperatures during the time of the winter minimum and summer maximum. Any changes in warming and cooling rates during the spring and fall are too small to be detected.

Figure 5. Same as Figure 4 except for 32.5° to 50°.



3. Conclusions

Our paper presents values of the LT global and hemispheric maxima and minima temperatures, their dates of occurrence, and trends in these properties during the period from 1979 to 2009. We also compared the average annual temperature cycles for the 60.0–82.5° latitude bands for both hemispheres for the 1980–1989 and 2000–2009 time periods. The current data set showed most trends to be very small, although several were significant at the 5% level.

The best fit trend line for the date of occurrence of the global annual maximum and minimum temperatures do not show a statistically significant trend towards occurring later in the year (Figure 1(a)), while the trends in the magnitudes of the temperatures also were positive but in this case statistically significant. When looking at these trends for each hemisphere individually (Figures 2 and 3), the only significant trend at the time of occurrence was for that of the Southern Hemisphere annual minima which showed a small trend towards later occurrences (Figure 3(b)), but each hemisphere did show an increase in the values of the annual maximum and minimum temperatures which did have significant trends. Previous analyses [2,3] using surface data for the annual cycle indicated a shift to earlier maxima. Although for a regional data set, Thomson [4] found a shift to later seasons. Figure 4 showed a small warming of the 2000–2009 period with respect to the earlier period in the Northern Hemisphere polar latitudes, along with a later occurrence of the maximum hemispheric average temperature. The Southern Hemisphere showed slightly colder winter and summer temperatures during the later period at the time when the average hemispheric temperature was near its maximum and minimum values, but showed little change between the two periods otherwise.

Overall, all trends were quite small, although some were statistically significant. In this paper, we do not draw any conclusions from these results as to causes which should be a thrust of following research. However, Stine *et al.* [2] indicated that the shift to an earlier annual cycle may be indicative of factors at play in the observations that are not handled in the models. We also note that models also fail in the amount of nocturnal warming compared to observations [12]. Given that the Stine *et al.* [2] simple energy budget analyses indicate the sensitivity to land use changes and the fact that the nocturnal boundary layer is more sensitive to land use changes [13], there may be a linkage. One path might be to construct an annual cycle in the surface data using only maximum temperatures. This may be more consistent with the LT annual cycle. Aside from changes in the timing of maxima and minima, the mean values have utility. The time of maxima and minima for each hemisphere as noted by Stine *et al.* [2] is a complex function of many variables but in the end represents an integrated value of the hemisphere's thermal inertia and response to forcing. Thus, it appears that dates of maxima and minima provide a metric that can be used to test climate models. The development of observational metrics such as presented here for the troposphere is important to providing a test for climate models on the general response to annual forcing. It is suggested that both surface and the LT annual cycle be studied together along with model simulations.

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