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An examination of 1997–2007 surface layer temperature trends at two heights in Oklahoma

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[1] This study assesses near surface lapse rates and temperatures over the past decade at two heights from the Oklahoma Mesonet. A statistically significant change in lapse rate was detected of -0.21 ± 0.09°C (10 m)$^{-1}$ per decade. The trend of nighttime lapse rate was about three times larger than the magnitude of trend of the daytime lapse rate. The lapse rate trends at the time of the daily maximum and minimum temperatures were larger during calm conditions. Significantly, changes of temperature trends at a single height were inconclusive when the data was not segmented by wind speed classes. For daily maximum and minimum station series at two heights, the temperature trends of these station series were the largest for daily minimum temperature at 1.5 m under calm conditions, and the second largest for daily minimum temperatures at 9.0 m under calm conditions. These observations document that monitoring long term near-surface daily minimum temperature trends at a single level on light wind nights will not produce the same trends as for long term temperature trends at other heights near the surface. **Citation:** Lin, X., R. A. Pielke Sr., K. G. Hubbard, K. C. Crawford, M. A. Shafer, and T. Matsui (2007), An examination of 1997–2007 surface layer temperature trends at two heights in Oklahoma, *Geophys. Res. Lett.*, *34*, L24705, doi:10.1029/2007GL031652.

1. Introduction

[2] Based on in-situ surface temperatures and near-surface wind data from NCEP/NCAR reanalysis, *Parker* [2004, 2006] found essentially the same trends of daily minimum surface temperature measured at shelter height for strong versus light wind conditions, and claimed that an urban bias had little effect on daily minimum temperatures since urban heat islands should be strongest in calm conditions. The results of *Parker* [2004, 2006] essentially require that the near-surface temperature trends are invariant in height (e.g., invariant lapse rate) under calm winds, with the same boundary-layer average temperature trends. In contrast, using fundamental concepts of how the nocturnal boundary layer distributes temperature with height, *Pielke and Matsui* [2005] showed that the nocturnal temperature trend under light winds is a function of height, and the near-surface (e.g., at 1.5 m above ground level) nocturnal temperature trend should be larger than that under strong winds, if the trends of boundary-layer averaged temperature in both light- and strong-wind cases are the same. This means that the sampling of near surface temperature trends at just one level on light wind nights will result in an overstatement of the actual average temperature change in the nocturnal boundary layer. *Walters et al.* [2007] found that even slight changes in overall nocturnal boundary layer cooling, such as from increased cloud cover, can cause the system to transition from nearly no turbulent mixing to a turbulent state thus producing particularly large changes in near-surface air temperatures.

[3] *Pielke and Matsui* [2005] and *Walters et al.* [2007] are modeling and analytic assessments. To examine the two hypotheses represented by *Parker* [2004, 2006] (which imply that a multi-decadal near surface temperature trend is invariant with height under light winds) and by *Pielke and Matsui* [2005] and *Walters et al.* [2007] (which concludes that these trends vary with near surface altitude under light winds), real-world observational data for at least two levels are needed.

[4] The Oklahoma Mesonet creates the opportunity to examine the temperatures measured at two-heights above ground level in a statewide, world-class environmental monitoring network starting from 1994 [*McPherson et al.*, 2007]. The Oklahoma temperature data are densely distributed, high-quality, and nearly free of inhomogeneity issues caused by observational timing, instrument biases, operational practices, and sparse sampling in sounding data sets [*Free et al.*, 2005]. Data from the Oklahoma Mesonet also include the time of occurrence for both the daily maximum and daily minimum temperature with continuous hourly-averaged data.

[5] This study is a first investigation on a regional scale of near-surface, two-height temperature observations to evaluate the lapse rate variation and trends. Our analysis includes the near-surface wind effect to test the hypotheses on whether lapse trends are different during light wind versus strong wind nights [*Pielke and Matsui*, 2005]. We do not attempt to attribute any trends to particular climate forcings [*Pielke et al.*, 2007], because the length of time series is limited and the knowledge of anthropogenic and natural external forcing in Oklahoma is not adequate.

2. Data and Analysis Method

[6] Among the many variables collected, the Oklahoma Mesonet provides near-surface temperatures and wind speeds observed at two heights, 1.5 m and 9.0 m, and

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2.0 m and 10.0 m, respectively. The selection of stations used in this study was based on the availability of adequate data free of inhomogeneities as determined by subjecting the monthly temperature series within our study period to a standard normal homogeneity test [*Alexandersson and Moberg*, 1997]. The tests excluded surface air temperatures from some stations during a time (approximately 1994 to 1996) when the algorithm for processing signals from surface temperature sensors was not finalized [*Shafer et al.*, 2000]. After maximizing the spatial and temporal coverage, a quality-assured subset of 49 stations was selected for the period June 1997 to May 2007.

[7] Hourly and daily data of temperatures and wind speeds, and the time of occurrence of daily maximum and minimum temperature are used in this study. We retained missing data without any filling; monthly data were excluded when more than 5 days were missing in a month (which was less than 2% of the total months). Outlier screening was unnecessary in this data set. The lapse rate is expressed as $-\frac{\partial T}{\partial z}$, and is evaluated by using the temperature observed at two heights (1.5 m and 9.0 m) and was converted to units of degrees °C $(10\ \text{m})^{-1}$. All lapse rates shown in this manuscript were calculated by synchronized observations of hourly temperature.

[8] The mean wind speed of the two heights was used to classify wind status at the time of the daily maximum (TX) or minimum (TN) temperature as windy (75% percentile or above) or calm (25% percentile or below). This means that there are approximately 7 windy and 7 calm days each month used to produce the monthly series. The air temperatures for daytime and for nighttime were calculated from the sunrise hour through the following 12 hours for daytime and the other 12 hours as nighttime during any calendar day. The anomalies for temperature series and/or lapse rate series were departures from monthly climatology for the entire study period. The regional time series was produced by using an equal weighted station average from each station using the values available.

[9] Due to our limited temporal samples, 120 samples in 10 years, we evaluated the statistical significance of regional temporal trends and individual station trends using the adjusted standard error and adjusted degrees of freedom method (AdjSE + AdjDF) which previously was used to evaluate trends from a 14-year monthly radiosonde time series [*Santer et al.*, 2000; *Seidel and Lanzante*, 2004], This approach is a modification of the ordinary least squares linear regression to substitute the effective sample size, n_e, for n, the number of time samples in a regression time series, in an attempt to account for the effect of temporal autocorrelation in the anomaly time series or its residual series,

$$n_e \approx n\frac{1-r_1}{1+r_1} \tag{1}$$

The variable r_1 is the lag-1 autocorrelation coefficient calculated from the least-squares linear regression residual series as suggested by *Santer et al.* [2000]. The extent of sample number reduction from n to n_e depends upon the strength of the autocorrelation.

[10] A strong autocorrelation means that individual values in the sampling series are far from being independent, so that the effective number of independent values must be much smaller than the sample size. Whether a trend in a time series $x(t)$ is significantly different from zero is tested by computing the relation between the estimated trend (b) and its adjusted standard error (s_b),

$$t_b = \frac{b}{s_b} \tag{2}$$

Under the assumption that t_b is distributed as a Student's t, the calculated t statistic is then used to determine the p-values for judging a null hypothesis (no significant trend) for a stipulated significance level α (say 0.05) and $n_e - 2$ degrees of freedom. This approach was justified by examining the lag-1 versus higher lag values of the partial autocorrelation function in the series that we analyzed in this study. Note that the 95% confidence intervals are adjusted by inverting the Student's t distribution to obtain n_e and p-value = 0.975 (two-tailed). In the following discussion, significance of a temporal series or station series is assumed at the 5% level unless otherwise specified.

3. Results and Discussion

[11] Figure 1 is a plot of the regional monthly anomaly series of daily maximum (TX), daily minimum (TN) temperatures, daily mean (TG) temperatures, and difference series of TG between 9.0 m and 1.5 m during the period June 1997 to May 2007. TG is determined as an arithmetic average of TX and TN. For each individual time series in Figures 1a, 1b, 1c, 1d and 1e, all adjusted p-values are much larger than 0.05, thus, no significant trends were found for TX, TN, and TG, respectively. Because the time of occurrence of TX (or TN) at the two heights are not, in general, the same, a simple difference in time series between TX or TN at two heights is inappropriate.

[12] The time series of differences in daily mean temperature ($\text{TG}_{9.0\text{m}} - \text{TG}_{1.5\text{m}}$) exhibits an increasing trend (+0.168°C per decade). The difference reduces noise levels by subtracting variability common to $\text{TG}_{9.0\text{m}}$ and $\text{TG}_{1.5\text{m}}$ including possible instrument biases. This approach facilitates identification of differences in real trends that may exist between the two time series.

[13] Note the result in Figure 1f suggests that mean temperature at 9.0 m had a larger warming trend or a smaller cooling trend than that of the mean temperatures at 1.5 m. To determine whether the mean difference series shown in Figure 1f reflects the variation and trends for the temperatures at the two heights, a time series plot of the monthly means of absolute lapse rate (LR) is shown in Figure 2a. A clear seasonality is evident in the absolute LR series especially during nighttime. The seasonal variability of absolute LR is affected by the mixed layer during daytime and by the nocturnal boundary layer during nighttime. After removing seasonality, the LR anomalies all displayed significant decreasing trends in daily, daytime, and nighttime lapse rates (Figures 2b and 2c and 2d).

[14] The results indicate that the trend of nighttime LR, -0.33°C $(10\ \text{m})^{-1}$ per decade, was three times larger than the trend for the daytime series (-0.09°C $(10\ \text{m})^{-1}$ per decade). In addition, the variability of the nighttime LR, for

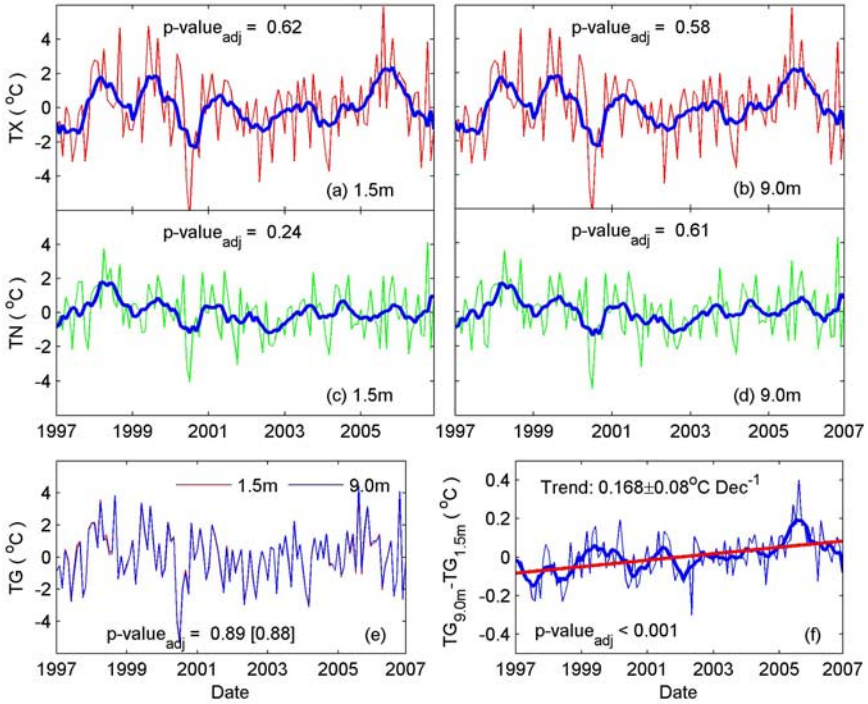

Figure 1. Time series of monthly mean temperature anomalies over June 1997–May 2007 in Oklahoma: (a) daily maximum temperature (TX) at 1.5 m, (b) daily TX at 9.0 m, (c) daily minimum temperature (TN) at 1.5 m, (d) daily TN at 9.0 m, (e) daily mean temperature (TG) at 1.5 m and 9.0 m, and (f) difference series of TG between 9.0 m and 1.5 m. The thick curves are time series of 7-month running averages (used as a smoother) of original monthly data. The straight line is a linear fit to the data and p-value$_{adj}$ refers to the adjusted p-values from the AdjSE + AdjDF method. The ± values define the 95% confidence intervals for trends.

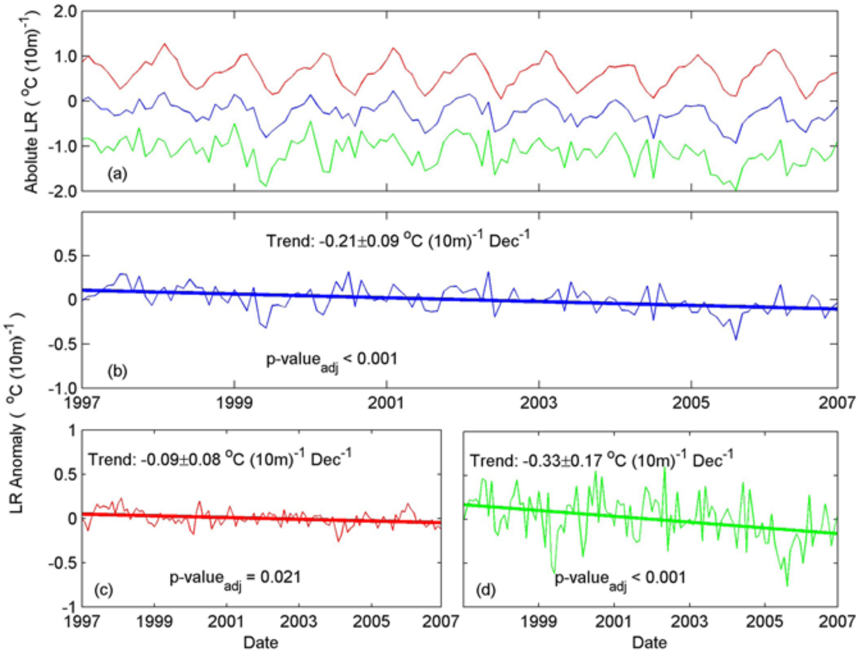

Figure 2. Time series of monthly mean lapse rate (LR) in Oklahoma: (a) absolute daily (blue), daytime (red), and nighttime (green) lapse rates; (b) daily anomaly derived from 24-hour averaged over two heights; (c) daily daytime anomaly; and (d) daily nighttime anomaly. The straight lines are least squares trends with adjusted p-values shown. The ± values define the 95% confidence intervals for trends.

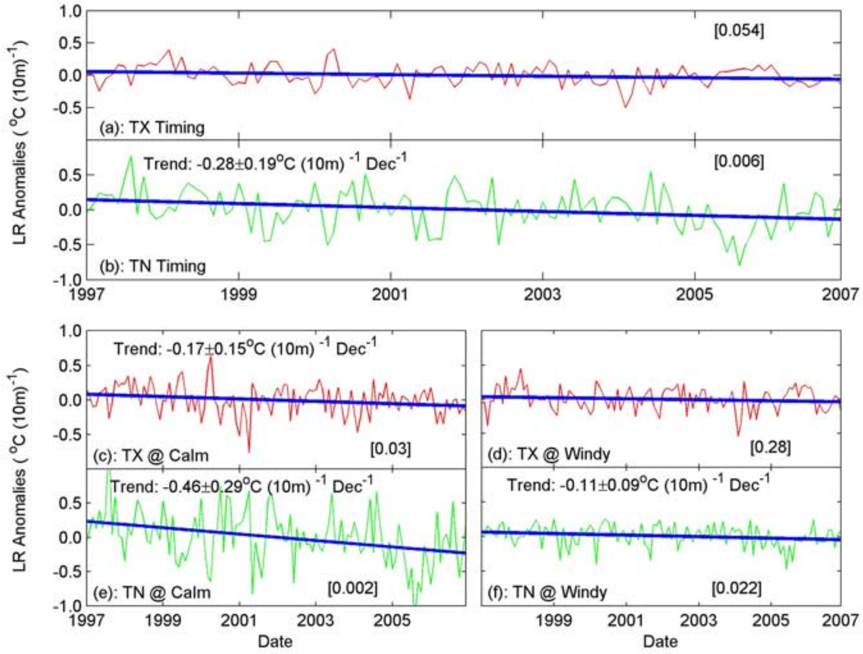

Figure 3. Monthly mean lapse rate anomalies at the time of occurrence of: (a) daily TX and (b) daily TN at 1.5 m. The time series in Figure 3a was classified as: (c) the 7 calmest days (25 percentiles) series, and (d) the 7 windiest days (75 percentiles) series. The time series in Figure 3b was classified as: (e) the 7 calmest days (25 percentiles) series, and (f) the 7 windiest days (75% percentiles) series. All weighted lines are linear trends. Values in square brackets are adjusted p-values and the ± values define the 95% confidence intervals for trends.

example, was much larger than that of daytime LR. Likewise, the trend of daily LR was close to the average of the daily nighttime and daytime trends (Figures 2b–2d) as should be expected.

[15] To further examine the lapse rate trends in Oklahoma, the hourly winds were classified as "windy" (upper 25 percentile) or "calm" (lower 25 percentile of wind speeds). The wind effects on the nocturnal surface temperature trends are hypothesized to be important as presented by *Pielke and Matsui* [2005], wherein they concluded the same surface temperature trends should not be expected in near surface layers on windy and light wind nights — even if the overlying boundary layer has the same layer-averaged cooling rate. However, actual observed wind speeds were not used in their study.

[16] Figures 3a and 3b illustrate the time series of the monthly lapse rate anomalies when timed to the hour of the day when TX at 1.5 m occurred and the hour when TN at 1.5 m occurred. In this case, the linear trend of LR at the time of TX was not statistically significant (adjusted p-value = 0.054), but the LR at the time of TN had a significant trend, $-0.28°\mathrm{C}\ (10\ \mathrm{m})^{-1}$ per decade. For the LR anomalies timed to TX, the trend under calm conditions, $-0.17°\mathrm{C}\ (10\ \mathrm{m})^{-1}$ per decade, was two times larger in magnitude than the trend during windy conditions. Moreover, the trend magnitude of LR under calm conditions at the time of the TN was nearly four times larger than that under windy condition (Figures 3e and 3f). Our results imply that wind effects on LR trends during nighttime were much stronger than wind effects on LR trends during daytime. This result and the findings shown in Figure 2 for averaged daytime or nighttime LR are consistent with the hypothesis derived from the analytic study by *Pielke and Matsui* [2005] that the temperature trends are a function of height in the nighttime surface layer under light winds.

[17] To further examine the wind effects on the daily TX and TN series; we used the daily wind speeds at two heights for classifying the windy and calm conditions. This approach is different from using hourly wind speeds for the LR series because of the timing issues for daily TX and TN for the two heights, as mentioned earlier. Geographically averaged TX and TN series displayed no significant overall trends at 1.5 m and 9.0 m (Figures 1a–1c). When individual station series of daily TX and TN at two heights were examined, no significant trends were detected for windy conditions (not shown) and no significant trends for daily TX station series under calm conditions (Figures 4a and 4b). However, 15 stations out of 49 stations for daily TN at 1.5 m and 7 stations for daily TN at 9.0 m had significant positive trends (Figures 4c and 4d). This result suggests that the wind effects were the largest for daily TN at 1.5 m under calm conditions, and the second largest effect shown was for daily TN at 9.0 m under calm conditions.

4. Conclusion and Summary

[18] We have examined a two-level near surface air temperature data set and produced a climatology of surface layer temperatures based on data from 1997–2007 in Oklahoma. Several insights were gained through our analysis. First, the near surface air temperatures of Oklahoma changed over the period 1997 to 2007 but a single level surface temperature anomaly was inadequate to quantify the variation. We also introduced a new temperature assessment

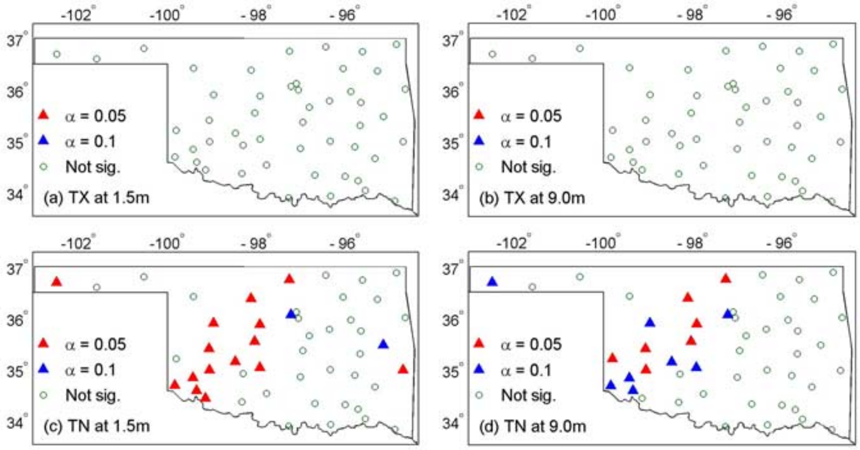

Figure 4. Statistical significance of individual station trends of daily TX and TN under calm conditions: (a) TX at 1.5 m, (b) TX at 9.0 m, (c) TN at 1.5 m, and (d) TN at 9.0 m. The α refers to the significant levels. Triangles with apex up indicate warming trends of station time series. The blank circles refer to the station series not statistically significant. A total of 49 stations were used in this study.

metric — *the near surface lapse rate*. For this time period, a significant trend of about -0.21 ± 0.09°C (10 m)$^{-1}$ per decade was discovered in the Oklahoma time series. The trend of daily nighttime lapse rate was about three times larger in magnitude than the trend of daily daytime lapse rate. The cause of such significant lapse rate trends while not significant for any individual TX and TN at the two heights can be explained by the better signal to noise ratio in the lapse rate time series, which, by simultaneously including common variability, makes its trends more detectable than the trends in the TX and TN at individual heights (i.e. two data samples are available to detect trends rather than data from just one level).

[19] We also quantified the wind effects on near surface temperatures. As a result, the lapse rate trends at the time of the daily maximum and minimum temperatures were larger during calm conditions, especially for the lapse rate trend for the time of the daily minimum temperatures. The magnitude of these trends does, however, vary from calm to windy conditions. Therefore, our analysis of real-world data supports the hypothesis and results from an analytical study by *Pielke and Matsui* [2005]. Also, because of the availability of data at two observation heights in our study, we present a more comprehensive assessment of wind effects than previous studies limited to temperature at only one height, e.g., *Parker* [2004, 2006].

[20] Our results also indicate that the 1.5 or 2 m minimum long term temperature trends over land are not the same as the minimum long term temperatures at other heights within the surface boundary layer (e.g. 9 m), even over relatively flat landscapes such as Oklahoma. For landscapes with more terrain relief, this difference is expected to be even larger. Therefore, the use of minimum temperatures at 1.5 or 2 m for interpreting climate system heat change is not appropriate. This means that the 1.5 to 2 m observations of minimum temperatures that are used as part of the analysis to assess climate system heat changes (e.g., such as used to construct Figure SPM-3 of *Intergovernmental Panel on Climate Change* [2007] and of *Parker* [2004, 2006] study) lead to a greater long term temperature trend than would be found if higher heights within the surface boundary layer were used. Our exploration of near surface lapse rate changes including wind effects should, therefore, be extended to longer-term time series as well as cover larger spatial areas.

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