Diurnal and seasonal cycles of trends of surface air temperature

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[1] A new technique was recently developed to study seasonal cycles of climatic trends of expected values, variance, skewness, and other statistical moments of climatic variables. Here we apply that technique to analyze the diurnal and seasonal cycles of trends of surface air temperature and its variability using hourly observations from nine geographically distributed meteorological stations in the United States for the period 1951–1999. The analysis reveals a complex pattern of trends in temperature and its variance at different times of the seasonal and diurnal cycle, showing warming trends for all stations during most times of the year and times of day, but with diurnal asymmetry of warming only in the warm half of the year. We found no correspondence between the trends in temperature and the trends in temperature variability. This analysis may be used as a prototype for developing the next generation of climate services that will be able to supply customers with detailed information about the first few moments of the statistical distribution of any meteorological variable for every day and hour of the period of observation. *INDEX TERMS:* 1620 Global Change: Climate dynamics (3309); 1694 Global Change: Instruments and techniques; 3309 Meteorology and Atmospheric Dynamics: Climatology (1620); 3394 Meteorology and Atmospheric Dynamics: Instruments and techniques; *KEYWORDS:* Diurnal cycle, seasonal cycle, climate change, climate variability, trends, temperature

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1. Introduction

[2] Determining useful ways to describe seasonal and diurnal cycles in meteorological parameters has always been a fundamental challenge to climatology and climate services. Hundreds of years ago, meteorologists began to employ simple statistics like monthly means, and, in the case of temperature, basic measurements such as the daily maximum and minimum. Nevertheless, long-term hourly (sometimes 3, 4, or 8 times per day) observations of many meteorological parameters for thousands of stations around the world have been archived in many climatic centers and the majority of these are now available in digital formats. This allows us a unique opportunity to gain a better understanding of observed climate change over diurnal and seasonal cycles. Here we present our initial results of studying the seasonal and diurnal patterns of climatic trends in expected value and variance of surface air temperature at nine selected meteorological stations in the United States for 49 years, 1951–1999. A technique, recently developed to analyze seasonal cycles in climatic trends [*Vinnikov et al.*, 2002], is used here to analyze temperature for every specific time (hour) of observation.

[3] We are not aware of any past work on this important problem, probably because the specific statistical tools needed for the analysis were previously unavailable. There have been a number of papers on the topic of the diurnal range of surface air temperature [e.g., *Karl et al.*, 1993; *Stenchikov and Robock*, 1995; *Easterling et al.*, 1997; *Dai et al.*, 1999], but they simply used the difference between the daily maximum and minimum temperatures as the definition of the diurnal range, and do not examine any of the details of the diurnal cycle. In fact, the most recent comprehensive analysis of observed climate change [*Folland and Karl*, 2001] restricts its analysis of the diurnal cycle to the relationship between maximum and minimum temperatures. Even though *Hansen et al.* [1995] point out that in their model, the diurnal temperature range calculated from maximum and minimum temperatures is very close to the true diurnal range, analysis of the full diurnal cycle is far more complex and interesting than the simple difference in the two numbers. For example, *Jin and Dickinson* [1999] examine techniques to combine twice-daily polar orbiting satellite observations of surface skin temperature with a model to produce the diurnal cycle of temperature. Com-

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Table 1. List of Stations, the World Meteorological Organization (WMO) Index Number, Latitude, Longitude, Altitude, Number of Observations (N), Skewness (Sk), Kurtosis (Ku), and Rejection Limits for Anomalous Observations[a]

City, State	Code	WMO	Latitude	Longitude	Altitude	N	Sk	Ku	s_1:s_2
Bismarck, ND	BIS	72764	46°47′N	100°45′W	503 m	400288	−0.15	2.83	−3.5:3.2
Boston, MA	BOS	72509	42°22′N	71°01′W	6 m	411093	0.24	3.08	−3.1:3.7
Chicago, IL	ORD	72530	41°59′N	87°55′W	201 m	395822	−0.01	2.84	−3.2:3.1
Milwaukee, WI	MKE	72640	42°57′N	87°54′W	205 m	400210	0.08	2.94	−3.3:3.4
New Orleans, LA	MSY	72231	30°00′N	90°15′W	1 m	389388	−0.45	2.99	−3.0:2.6
Salt Lake City, UT	SLC	72572	40°47′N	111°58′W	1288 m	429516	−0.18	3.16	−4.0:3.2
San Antonio, TX	SAT	72253	29°32′N	98°28′W	247 m	390356	−0.61	3.55	−4.4:2.7
Seattle, WA	SEA	72793	47°28′N	122°19′W	122 m	417626	0.16	3.65	−4.0:3.9
Washington, DC	DCA	72405	38°52′N	77°02′W	3 m	398129	0.04	2.91	−3.3:3.3

[a] s_1:s_2, in units of standard deviations.

prehensive climatic data on the seasonal cycle of observed surface air temperature measured at first-order meteorological stations can be used for interpretation of polar orbiting satellite microwave observations of surface skin temperature [e.g., *Williams et al.*, 2000].

2. Data

[4] Many first-order meteorological stations in the United States were relocated from within city limits to suburban airport locations in the 1950s. Climatic records of most of these stations are relatively homogeneous from that time. Here we use hourly observations of surface air temperature at nine such stations for 1951–1999: Seattle-Tacoma International Airport, Bismarck Municipal Airport, Boston Logan International Airport, Milwaukee Mitchell International Airport, Chicago O'Hare International Airport, Washington National Airport, Salt Lake City International Airport, San Antonio International Airport, and New Orleans International Airport (Table 1). We chose these stations because they had the most complete records of hourly surface air temperature observations for the past half century and for their relatively broad geographic distribution across the lower 48 United States. They also represent a range of altitudes and distances from major water bodies.

[5] Because of budgetary constraints, only three-hourly (instead of hourly) observations were archived at some of the stations for some of the years 1965–1972. But the total number of temperature observations, N in Table 1, is still large enough so that the influence of missing data on our analysis is small. The history files for these stations do not show significant changes of instrument locations.

3. Technique

[6] Let us consider the observed value of a meteorological variable $y(t, h)$ at day number $t = t_1, t_2, t_3,.., t_n$ and at specific observation times h, ($h = 0, h_1, h_2, h_3,.., H, H = 24$ hours), as a sum of the expected value $Y(t, h)$ and anomaly $y'(t, h)$:

$$y(t,h) = Y(t,h) + y'(t,h). \qquad (1)$$

Let us suppose that the climatic trends in the time interval (t_1, t_n) are linear, but they are different for different t and h.

$$Y(t,h) = A(t,h) + B(t,h)\cdot t, \qquad (2)$$

where $A(t, h)$ and $B(t, h)$ are periodic functions:

$$A(t,h) = A(t+T,h), \qquad A(t,H) = A(t+1,0),$$
$$B(t,h) = B(t+T,h), \qquad B(t,H) = B(t+1,0), \text{ and}$$
$$T = 365.25 \; days.$$

For each specific observation time (h = constant) the model proposed earlier by *Vinnikov et al.* [2002] to analyze processes with a seasonal cycle in a linear trend, can be used:

$$A(t,h) = a_0(h) + \sum_{k=1}^{K}\left[a_k(h)\sin\left(\frac{2\pi kt}{T}\right) + b_k(h)\cos\left(\frac{2\pi kt}{T}\right)\right], \qquad (3)$$

$$B(t,h) = \alpha_0(h) + \sum_{m=1}^{M}\left[\alpha_m(h)\sin\left(\frac{2\pi mt}{T}\right) + \beta_m(h)\cos\left(\frac{2\pi mt}{T}\right)\right].$$

The unknown coefficients in equations (2) and (3) for each h can be estimated from the least squares condition:

$$\sum_{t=t_1}^{t_n}[y(t,h) - Y(t,h)]^2 = F[a_0(h),\ldots,a_K(h),b_1(h),\ldots,b_K(h),$$
$$\alpha_0(h),\ldots,\alpha_M(h),\beta_1(h),\ldots,\beta_M(h)] = \min. \qquad (4)$$

Vinnikov et al. [2002] discuss the choice of K and M; they should be chosen from independent considerations or should be estimated from analyses of the same data. The linear trend for each day of a year is $B(t, h)$. The estimates of $B(t, h)$ have a leap-year cycle. The trends in equation (2) do not have to be linear.

4. Trend Analysis

[7] The general approach to studying trends in climate variability was discussed by *Vinnikov and Robock* [2002]. The goal of this trend analysis is to reveal changes in the seasonal and diurnal cycles of surface air temperature and its variance during the second half of the 20th Century. We conducted the trend analysis using statistically controlled data, carried out as follows: (1) The parameters $a_0(h),..a_K(h)$, $b_1(h),.., b_K(h), \alpha_0(h).., \alpha_M(h), \beta_1(h),.., \beta_M(h)$ in the model (equations (2)–(4)) for $K = M = 6$ were estimated from data for each time of observation $h = 0, 1, 2, 3,.., 24$ hours. (2) The residuals $y'(t, h)$ and their squares $y'(t, h)^2$ were calculated for each observed $y(t, h)$. (3) The same model was applied to the time series of $y'(t, h)^2$ to estimate variances $\sigma(t, h)^2$, but assuming that for variances $B(t, h) = 0$ and $K = 4$. (4) Parameters of the statistical distribution of the standardized residuals $s(t, h) = y'(t, h)/\sigma(t, h)$ were estimated. The estimates

of the skewness (*Sk*) and kurtosis (*Ku*) coefficients for each station are given in Table 1. (5) Observed values $y(t, h)$ were considered valid if they satisfy the condition $s_1 < s(t, h) < s_2$. The threshold (s_1:s_2) was estimated to reject very unrealistic tales of the empirical statistical distribution of $s(t, h)$ but to not damage its shape. The intervals (s_1:s_2) for each station are given in Table 1. They cut approximately equal numbers of observations from the left and right sides of the distribution. The quality of the observed data was so high that only about 0.1% of the observed data were rejected.

[8] For the trend analysis of quality-controlled data, first we estimate parameters of the model (2–4) for the data $y(t, h)$ and for squares of residuals $y'(t, h)^2$. We then calculate trends of expected values of temperature and its variance, and calculate confidence intervals of the estimates of the trends. Finally we plot the results in a way that clearly illustrates these trends.

[9] The results of the calculations for each of the nine stations are presented in Figures 1–4. Figure 1 displays the average of the seasonal and diurnal patterns of expected values for 1951, the first year of record, and 1999, the last year of record. Both these years occupy the same position in the leap year cycle. If we ignore this four-year cycle, we can consider the estimates presented in Figure 1 as an approximation of the multiyear 1951–1999 average of expected values. Figure 2 gives the pattern of linear trends of expected values. Standard deviations shown in Figure 3 are calculated from the average of variances estimated for years 1951 and 1999. They approximately represent the multiyear average of variances for the 1951–1999 period of observation. The linear trend in variance from 1951 to 1999, expressed in terms of standard deviation, is shown in Figure 4. The shaded areas in Figures 2 and 4 indicate significant trends at the 95% level, meaning that the linear trend estimates for expected value and for variance, respectively, exceed two root mean square errors of the trend estimates. We should expect that these errors are underestimated and that the statistical significance of the trends is overestimated, because autocorrelation in the observed data, of an unknown magnitude, has been ignored.

5. Discussion and Conclusions

[10] Figures 1–4 reveal many significant changes in the seasonal and diurnal variation of temperature during the past half-century. Significant warming dominates the pattern for all stations, but the patterns are very complex. Diurnal asymmetry of the warming is evident for some stations, but only in the summer and fall, in agreement with an analysis using seasonal averages of daily maximum and minimum temperatures [*Karl et al.*, 1993]. However our new technique shows these patterns in much more detail. There is no correspondence between the trends in temperature and the trends in temperature variability.

[11] The standard deviation was largest in the winter at all times of day, but in the summer only in the daytime. There was no general trend in standard deviation, with as many positive trends as negative, and no evidence of diurnal asymmetry of the trends. However, Boston, Milwaukee, Chicago, and Washington all had upward trends in March and downward trends in April. Three of the stations, with the exception of Boston, have a significant warming at all times of the day in March. One interpretation of these patterns is to associate the trends of variance and mean temperature with an earlier arrival of spring, with its variable transitional weather and more fluctuation of warm and cold advection. In contrast, this transitional, variable weather is reduced in April, but there is a small cooling trend in April, but it is only significant in Washington and at some times in Boston. Our technique could also be applied to wind or other measure of storminess, such as precipitation, to investigate these patterns further. Here we present them only as an illustration of their potential for studying climate change in detail. For each region of the country, we now point out more specific findings:

[12] The Seattle plots demonstrate significant warming throughout most of the year, with the major exception during the month of December. This warming trend is generally in excess of 2°C/50 yr, which is more than five times the global average warming of 0.3°C/50 yr. Temperature increases are consistently higher in the nighttime and morning hours, which agrees with findings of other authors [e.g., *Karl et al.*, 1993]. Moreover, the warming is generally greatest during the nighttime in late winter and early spring. In contrast, the warming trend is smallest during the daylight hours in the warm half of the year (excepting the month of December). There are no major changes in standard deviation, except that it decreased during the month of November.

[13] It is very interesting that a maritime location would experience such significant warmth. We wonder whether changes in sea breezes during the evening and early morning hours could have a direct impact on these warming trends. A similar plot of wind speed and direction could illuminate the link between temperature trends and wind patterns. Therefore, we encourage the expansion the technique used in this article to parameters other than temperature.

[14] Bismarck, ND is representative of a strong continental climate. This location has an extreme warming trend (in excess of 5°C/50 yr) during the winter season, a rate of more than 10 times the global rate of the past century. Once again the warmth is greatest in the late evening and early morning hours. Moreover, during the summer months there is a significant cooling trend in the middle of the day, while no warming is apparent during any period of the summer months. Significant cooling is also apparent throughout October's diurnal cycle. Bismarck is an excellent example of the insight provided by the technique used in this article. Specifically, by evaluating trend variability on an hourly basis, one can gain a new dimension of understanding of how climate change has developed.

[15] Not surprisingly the standard deviation for Bismarck is twice as large as for Seattle. Moreover, Bismarck's diurnal range is nearly twice as large in the winter months, when dry Canadian air masses tend to dominate the region. In the summer, however, the long daylight and increased humidity diminished the diurnal temperature range. In terms of changes in standard deviation, there is a short period of increased variability in January, and decreased variability in spring and autumn daylight hours.

[16] Milwaukee and Chicago have very similar patterns of trends, variance, and trends of variance. This is not surprising, since they are both on the western shore of Lake Michigan, and are only 165 km apart. Nevertheless, their similarity gives us confidence that the method is reliable

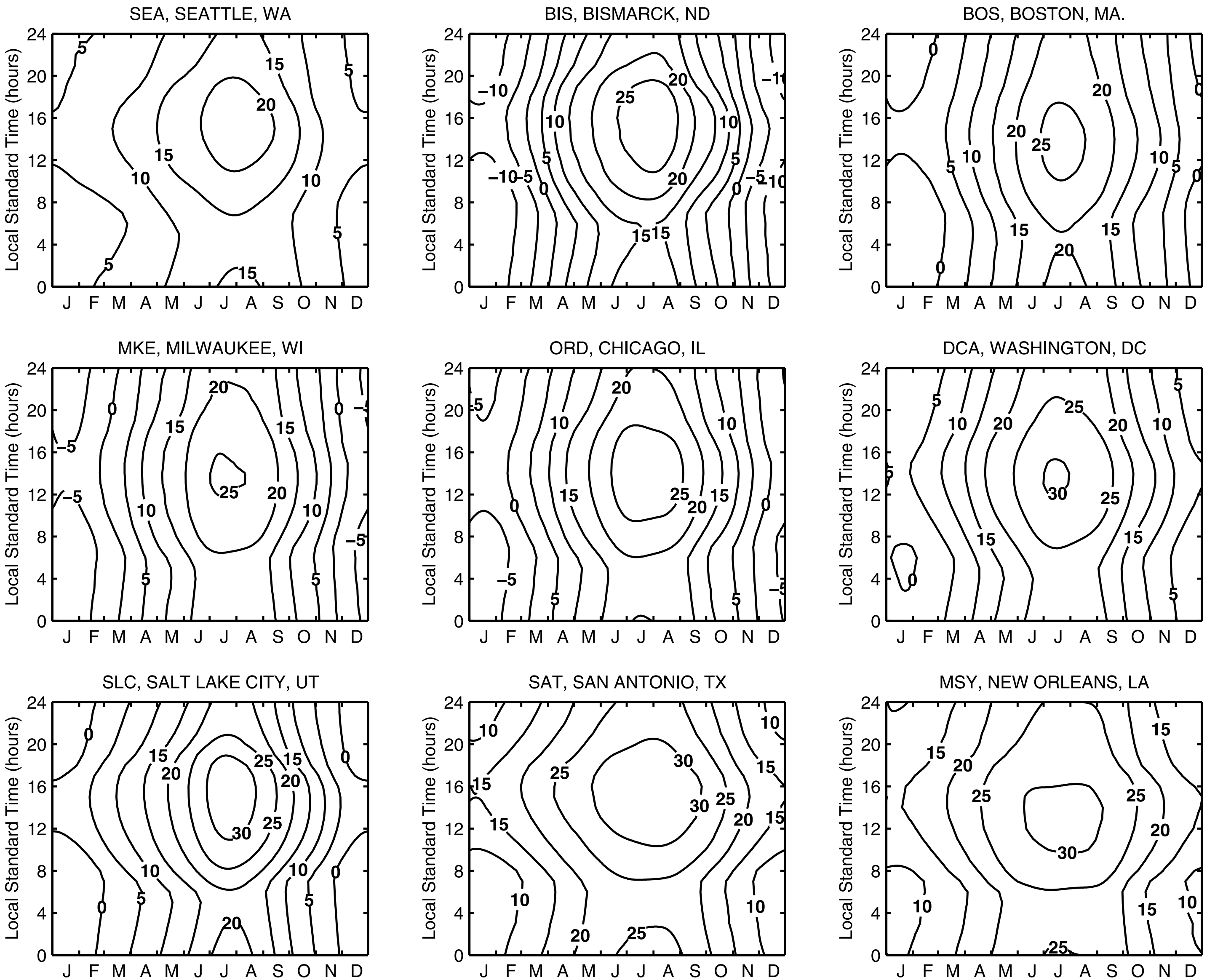

Figure 1. Mean temperature (°C) for 1951–1999 for nine U.S. stations (Table 1), calculated as the mean of the expected values for 1951 and 1999.

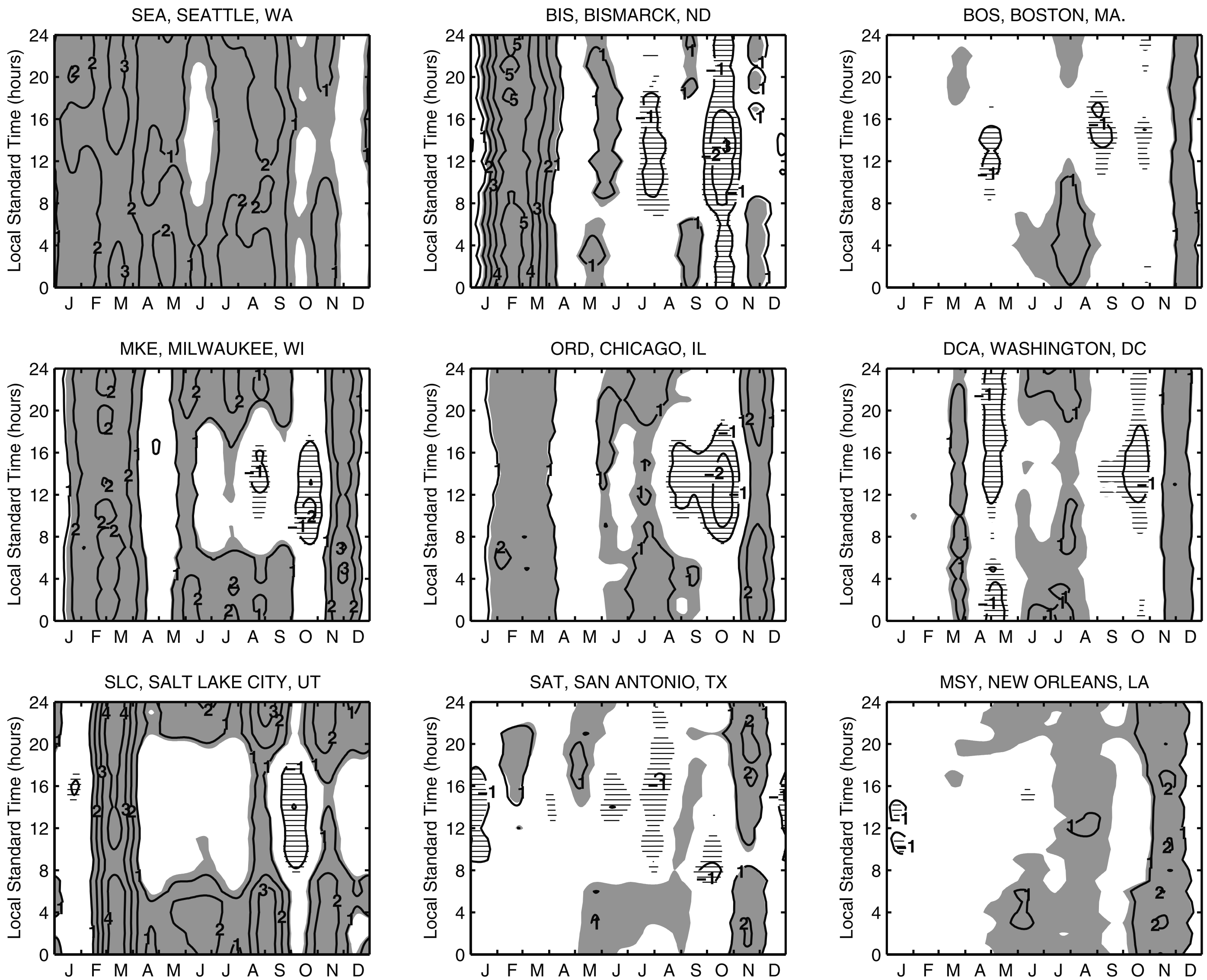

Figure 2. Trends of expected temperature for 1951–1999 for nine U.S. stations (Table 1), in units of °C/50 yr. Significant positive trends are shaded red (color) or gray (black and white), and significant negative trends are shaded blue or with horizontal lines.

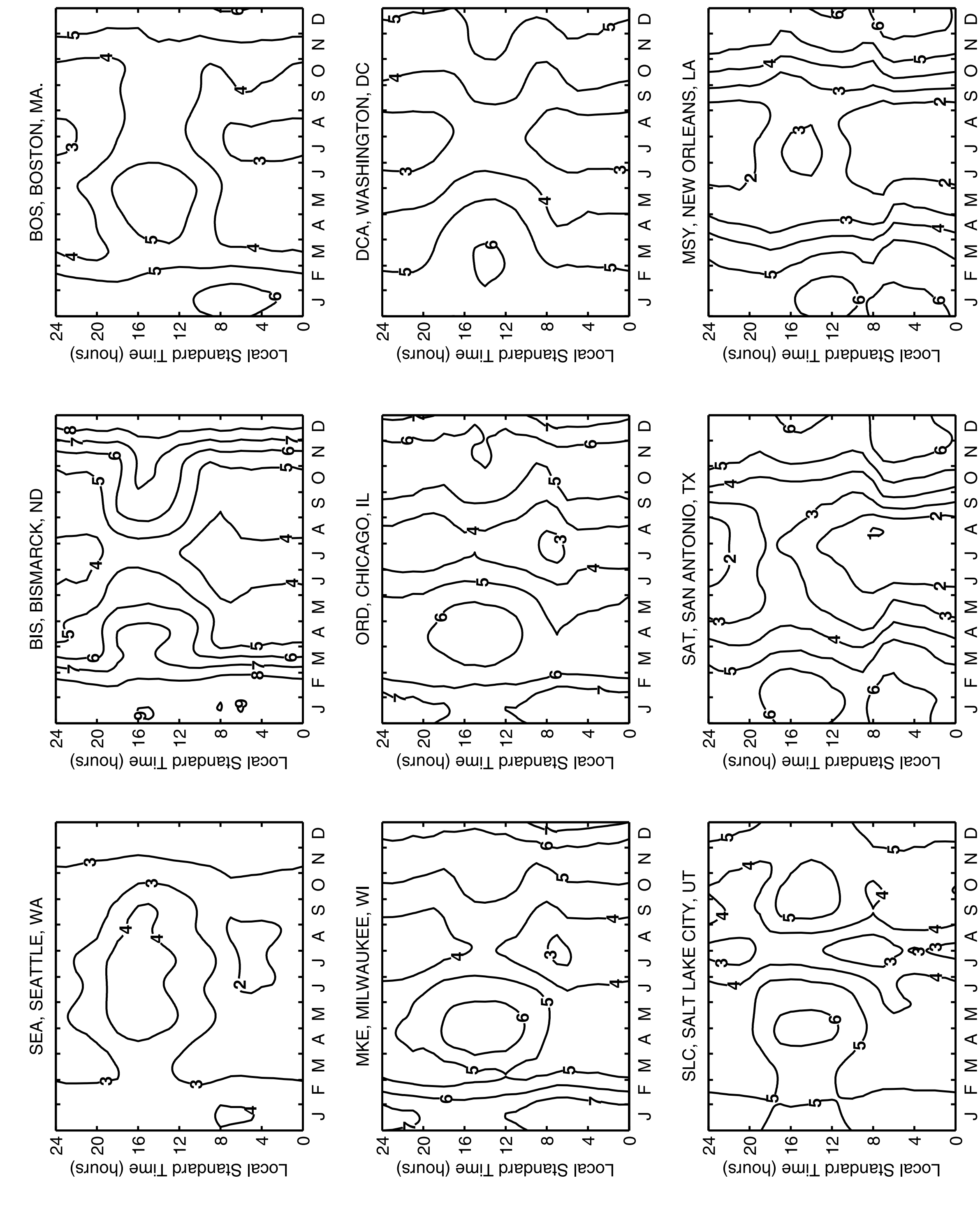

Figure 3. Mean standard deviations of temperature (°C) for 1951–1999 (calculated from averaged variance) for nine U.S. stations (Table 1).

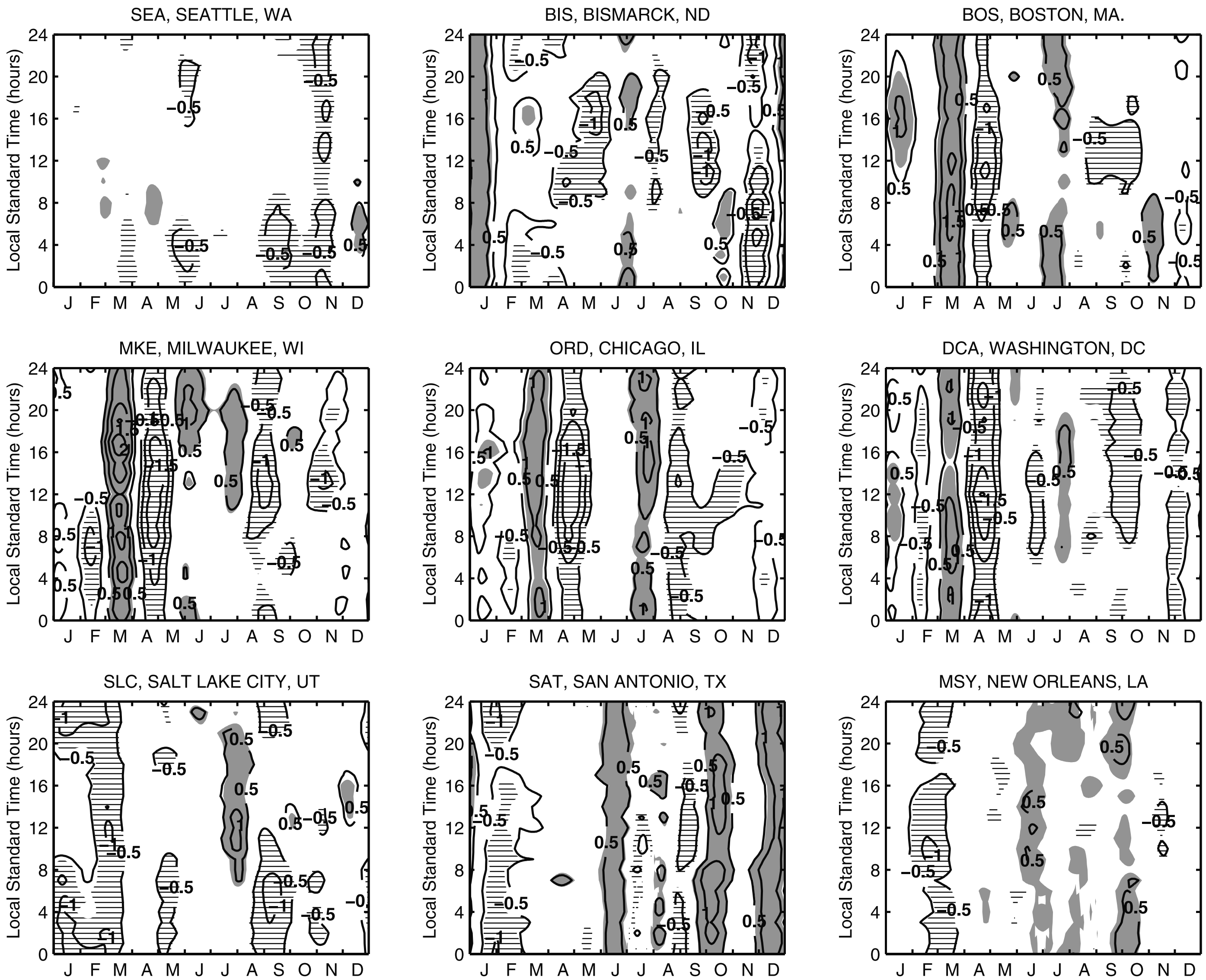

Figure 4. Change of standard deviation for 1951–1999 for nine U.S. stations (Table 1), in units of °C/50 yr. Significant positive trends are shaded red (color) or gray (black and white), and significant negative trends are shaded blue or with horizontal lines.

and stable. Both locations show a general warming trend, except for daylight cooling during the late summer and early autumn. The greatest warming trend is generally in the late autumn, when it exceeds 2°C/50 yr, with more moderate warming during the winter months. There is a slight increase in variance in March, followed by a decrease in late April and August. Variance is generally twice as high in the winter months, as compared to the summer. These two sites along the shore of Lake Michigan have slightly less variability than Bismarck, which we attribute to the influence of the lake.

[17] Boston and Washington also show similar patterns of diurnal temperature change, warming trends, and standard deviation, although they over 800 km apart. This indicates a large degree of homogeneity in climatic conditions along this section of the eastern coast of the U.S. There are some isolated periods with a significant warming trend during the evening and morning hours of the summer and late autumn, as well as some isolated periods of cooling in the spring and early autumn. The signal in Washington is a little stronger than Boston, which could be associated with its more continental location. Both sites have a slight increase in the standard deviation in March, followed by a decrease in April. There is also a warming cooling couplet in the midsummer and early autumn, followed a cooling trend with small warming, mostly in December and the summer months.

[18] We used Salt Lake City to represent an inter-mountain location. Large warming trends are most evident in the late winter. During the spring and summer months the warming only occurs during the evening and early morning hours. There is even a small period with cooling trends in the early autumn. It is interesting to note that of the seven regions analyzed in this study, six of them have demonstrated a cooling trend in the autumn, midday hours. Moreover, five of the regions demonstrate a significant warming during the winter.

[19] We analyzed San Antonio as an example of a location for the Southern Great Plains. This site does not exhibit any large period of warming or cooling. There are some indications of a warming trend in the late autumn, as well as in the morning hours during the summer. Conversely, there are indications of cooling during the midday hours in the summer. The standard deviation is intermediate compared to the other regions analyzed in this study. Not surprisingly, the amplitude of the standard deviation is many times larger in the winter than in the summer, since the summer is dominated by tropical air masses, while in the winter its weather vacillates between tropical and arctic air mass intrusion.

[20] New Orleans was chosen to represent a Gulf Coast site. Contrary to many of the other locations, the greatest warming trends occur in the summer and autumn months (no warming is apparent during the winter months), and there are no periods when a cooling trend is observed. During the period of record the standard deviation diminished during late winter; this may be associated with fewer cold intrusions. In contrast, there are indications of increased variability during the some periods in the summer.

[21] The trends in the expected temperature have a tendency to increase from south to north and from east to west over the United States (Figure 2). We see no systematic change in temperature variability (Figure 4), except for the late winter/early spring dipole in the northeast United States discussed earlier.

[22] Figures 1–4 give a comprehensive picture of the observed changes in hourly temperature and its variability during the last 50 years at many U.S. stations. They also show which parts of these changes were statistically significant. The observed changes are very complicated. They cannot be interpreted as simply as the results of earlier research of trends in monthly averages of maximum and minimum temperature. The results we present do not contradict conclusions of the earlier research, yet they demonstrate how our technique can provide valuable new insight and more detailed interpretation of the climatic changes.

[23] Representativeness of the first-order stations at major airports is always questionable. For example, *Foster and Leffler* [1981] found that the Washington National Airport station (DCA) is inside of Washington, DC's heat island. But as compared to the temperature records of other meteorological stations in the region (the first-order station BWI, Baltimore, MD airport; an urban station, Baltimore Customs House; and a rural station, Woodstock, MD) we found that its heat island is stable and the station can be used in trend analyses.

[24] Our technique allows the estimation of the expected values of the main moments of the statistical distribution of meteorological variables for every hour h of every day t from the period of observations. The technique is not sensitive to gaps in the data. Polynomial or other functions can be used instead of linear trends. The technique can be extended for the case when times of observations are different for different parts of the record. This analysis may be used as a prototype for developing the next generation of climate services, which will be able to supply customers with detailed information about moments of the statistical distribution of many meteorological variables for each day and each hour of the period of observation.

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