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TRENDS IN TIME-VARYING PERCENTILES OF DAILY MINIMUM AND MAXIMUM TEMPERATURE OVER NORTH AMERICA

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1. INTRODUCTION

Over the last century, estimated trends in annual mean air temperature show that Earth has experienced a warming of approximately 0.6°C/100yr (Jones et al., 2001). Over the last half-century, the estimated warming rate has increased to 0.9°C/100yr for (daytime) maxima and 1.8°C/100yr for (nighttime) minima (Easterling et al., 1997). While these trends can have profound implications (e.g., Strzepek and Smith, 1995; McCarthy et al., 2001; Root et al., 2003), annual and seasonal mean temperatures do not incorporate the vast distributional information that can be derived by using daily climatic data, the original resolution of the instrumental data record. Related information on trends in climatic variability (Karl et al., 1995; Robeson, 2002a) and extremes (Karl and Easterling, 1999; Easterling et al., 2000) also must be considered when evaluating the magnitude and impacts of recent climatic change. Still, relatively little research has estimated how parameters of daily air-temperature frequency distributions other than the mean have changed with time or how they interact with one another (Robeson, 2002a).

The importance of noncentral portions of air-temperature frequency distributions certainly has been documented (e.g., Katz and Brown, 1992; Mearns et al., 1984) and climate-change induced variations in extreme air-temperature events are receiving wider attention (e.g., Cooter and LeDuc, 1995; Easterling et al., 2000; Gaffen and Ross, 1998; Karl and Easterling, 1999; Meehl et al., 2000). Frequently, studies of extreme air-temperature events have used threshold temperatures (e.g., 0°C or 95°F) or have been driven by a particular application, such as agriculture or human health. These approaches clearly are valid and useful. In addition to these approaches, however, a comprehensive procedure for the simultaneous detection of trends in all portions of air-temperature frequency distributions is needed to capture the full range of climatic change. By examining trends in time-varying percentiles of daily minimum (T_{min}) and maximum temperature (T_{max}), this research documents changes in the entirety of air-temperature frequency distributions across North America during the last half century. The simultaneous examination of the entire air-temperature distribution is particularly useful for evaluating how the upper and lower tails of the air-temperature distribution are changing relative to central tendency.

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2. METHODS

Analyses of trends in time-varying percentiles provide flexible alternatives to traditional approaches that focus on variations in central tendency, usually the mean. In addition, analysis of changes in low-probability events (such as the 5^{th} or 95^{th} percentile) can provide valuable information for climate-impact studies where extreme events are important (Meehl et al., 2002). In this research, percentiles are estimated on a monthly basis. When estimated over seasonal or annual periods, lower-tail percentiles typically are drawn from the colder months and upper-tail percentiles are drawn from warmer months. For instance, in an analysis of percentiles for the spring season (Mar, Apr, May), the 10^{th} percentile for the season typically would be drawn from early or mid-March, while the 90^{th} percentile would be drawn from mid- or late-May. As a result, percentiles created in this fashion are not representative of the entire season.

For each station, percentiles from the 5^{th} to the 95^{th} (in 5 percentile increments) were estimated for each month of every year. From the time series of percentiles, linear trends over the period of record were estimated using least-squares regression. The trends were then interpolated onto a hexagonal equal-area grid (Sahr et al., 2003) using spherical thin-plate splines (Wahba, 1981). Cluster analysis then is used to identify regions of North America that have homogeneous percentile trends over the twelve months. The nature of the clustering methods, as well as previous work with climate data (Kalkstein et al., 1987; Gong and Richmond, 1995; Jackson and Weinand, 1995) suggests that average linkage is the most appropriate linkage method for identifying cohesive regional percentile trends. Comparisons with single-linkage show that average-linkage indeed identifies several larger homogenous clusters, while single-linkage tends to identify small clusters of unusual trends along the periphery of the percentile-trend space.

3. DATA

To examine trends in time-varying percentiles, high temporal resolution data are needed over relatively long periods of time. Relatively high-quality daily T_{min} and T_{max} data have recently become available for much of the United States and Canada. The data used here are derived from (i) the daily United States Historical Climatology Network (HCN) archive (Easterling et al., 1999), which contains 1062 stations over the 48 contiguous states, (ii) the daily Historical Adjusted Climate Database for Canada (HACDC; Vincent et al., 2002), and (iii) a subset of the Alaska stations from the

Global Daily Climatology Network (GDCN, 2002), selected for long-term, nonurban locations. The combination of the daily HCN, HACDC, and Alaska subset of the GDCN produces a network of 1324 stations that have records spanning 1948 to 2000 (see Fig. 1 for spatial distribution of stations; not all stations had data available for all months, but all stations had less than 20% missing data for the months used). The daily HCN and Alaska stations have been selected for their long-term quality, based on criteria such as consistent observation times, low potential for urban bias, and other quality assessments that were developed for the monthly HCN. The Canadian station data already have been homogenized (Vincent, 1998) and, therefore, provide a useful test of whether stations within an adjusted data set have different trends from those that have not been adjusted (i.e., differential trends near the U.S.-Canada border).

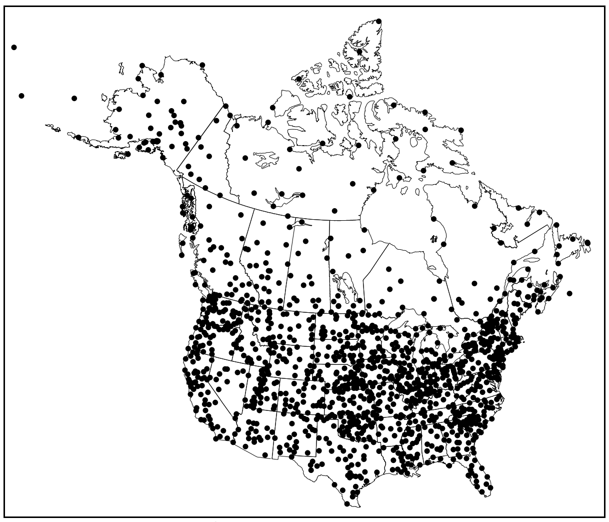

Fig. 1. Location of stations with daily air temperature available during the period 1948 to 2000.

4. RESULTS AND DISCUSSION

Trends in mean air temperature usually are analyzed at annual and seasonal timescales (e.g., Easterling et al., 1997; Jones et al., 2001). Trends in time-varying percentiles, as noted above, are most effectively analyzed at the monthly timescale, which adds both depth and complexity to the analysis of recent climatic change. Further, because any number of percentiles can be analyzed, numerous maps and summaries of percentile trends can be evaluated. A useful approach is to examine trends in both tails of the air-temperature distribution, such as the 10th and 90th percentile, while also evaluating the trend in the center of the distribution (50th percentile, or median). To demonstrate the comprehensive nature of percentile trends, I first show maps of trends in the 10th, 50th, and 90th percentiles of T_{min} over North America from 1948 to 2000 during April (Fig. 2). Many locations in western North America have stronger warming in the 10th percentile of T_{min} than in the 90th percentile. In addition, some locations such as

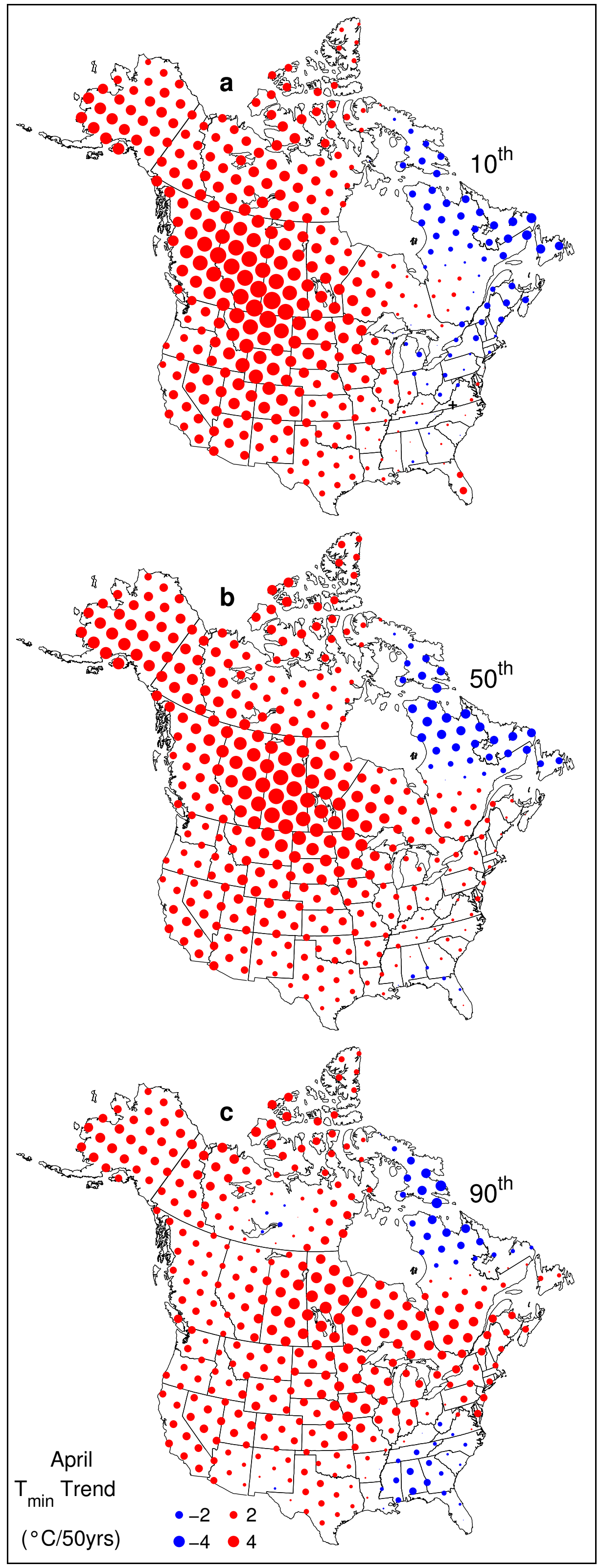

Fig. 2. Maps of trends (°C/50yr) in time-varying percentiles of minimum air temperature (T_{min}) during April from 1948 to 2000: (a) 10th percentile, (b) 50th percentile, and (c) 90th percentile.

the southeastern U.S. show little change in the 10th percentile while there is modest cooling in the 90th percentile. Overall, these patterns show a tendency towards a less variable thermal climate at these locations during April – the lowest April temperatures are warming at a faster rate than the highest April temperatures (which, in some cases, are cooling). When air temperature's central tendency is increasing, reduced air-temperature variability is the expectation, but far from the rule (Karl et al., 1995; Robeson, 2002a).

When spatially averaged over North America (excluding Mexico) and plotted in month-percentile space, trends in all time-varying percentiles from 1948 to 2000 are summarized effectively (Fig. 3). From January to April, all T_{min} percentiles – nearly the entirety of the daily T_{min} frequency distribution – has experienced warming of over 1°C/50yr; however, much of the lower half of the distribution has experienced warming of over 2°C/50yr (Fig. 3a). The most intense warming in T_{min} over the last half-century has been concentrated in the lowest temperatures during January to April. Unlike the other winter months, December shows little warming. Percentile trends for T_{min} for the rest of the year are much weaker and even negative for some percentiles during October and November.

Continental-scale averages of trends in time-varying percentiles of T_{max} from 1948 to 2000 also show the greatest warming during colder months; however, the warming is of lesser magnitude (1-2°C/50yr) and is not restricted to the lower percentiles (Fig. 3b). Warming in T_{max} percentiles is most intense during February and March, with slightly higher warming in the upper percentiles. Modest cooling occurs in the autumn months and is again spread relatively evenly across the T_{max} frequency distribution.

The continental-scale averaging used above obscures coherent spatial patterns that exist in the percentile trends. Average-linkage cluster analysis suggests that three primary spatial patterns exist for both T_{min} and T_{max}, with two of the three patterns dominating approximately 95% of North America (Figs. 4-5). For T_{min}, an eastern North America pattern (cluster 1 in Fig. 4, which represents 37% of North American land area) had modest warming trends during February and March, but very weak trends at other times of year. The western North America pattern for T_{min} (cluster 3 in Fig. 4, which represents 56% of North American land area) had intense warming during January through April, with trends exceeding 2°C/50yr for all percentiles. The lower tail of the T_{min} frequency distribution for this pattern, however, had the strongest warming, with trends exceeding 3°C/50yr for the lower percentiles from January through March. Trends in T_{min} in western North America at other times of year are mostly positive; however, weak cooling occurred during October and November. The T_{min} pattern representing a small part of northeastern Canada (cluster 2 in Fig. 4a) has mixed signals, with strong to modest cooling during colder months and weak warming in warmer months.

Three primary spatial patterns also exist for T_{max} trends over the last half century. Unlike those for T_{min}, however, nearly all of the contiguous USA and part of eastern Canada are in one dominant pattern (representing 53% of North American land area). The other dominant pattern extends over Alaska and most of western and central Canada, representing 45% of North American land area. The contiguous-USA/eastern-Canada pattern (cluster 1 in Fig. 5) has moderate warming in the upper percentiles of T_{max}

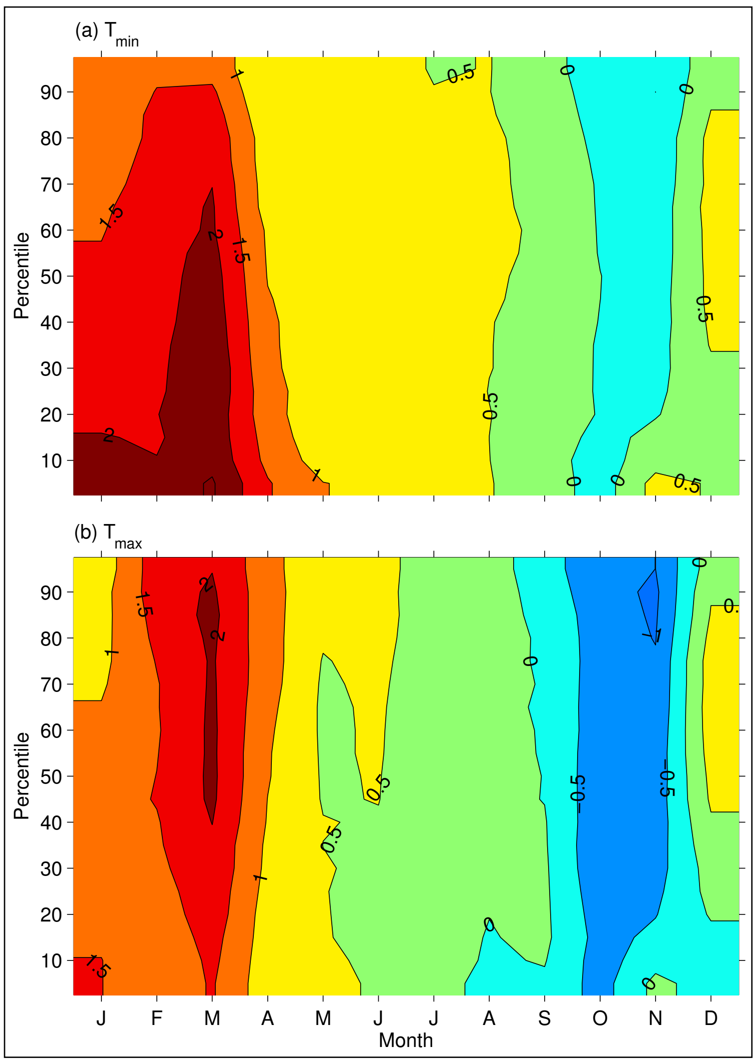

Fig. 3. Spatially averaged trends (°C/50yr) in time-varying percentiles of (a) T_{min} and (b) T_{max} over North America from 1948 to 2000.

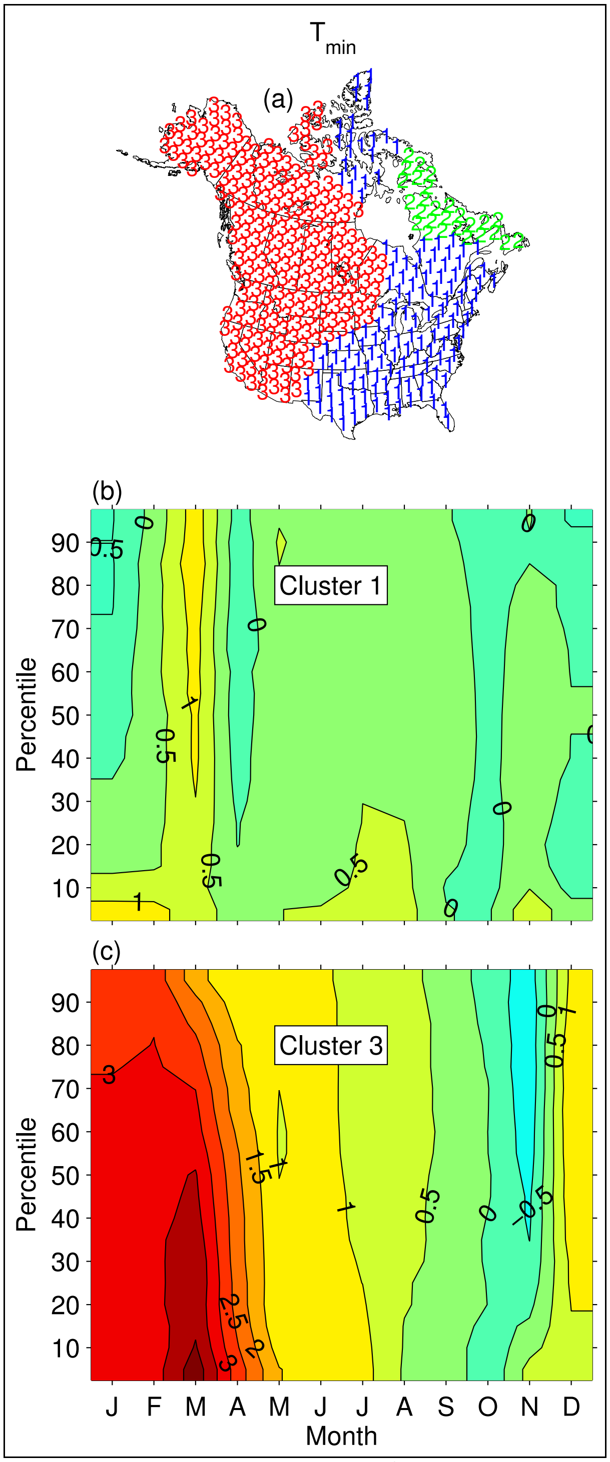

Fig. 4. Average-linkage clusters of spatially averaged trends (°C/50yr) in time-varying percentiles of T_{min} over North America from 1948 to 2000: (a) map of locations falling within the three primary clusters, (b) spatially averaged percentile trends for cluster 1, and (c) spatially averaged trends for cluster 3.

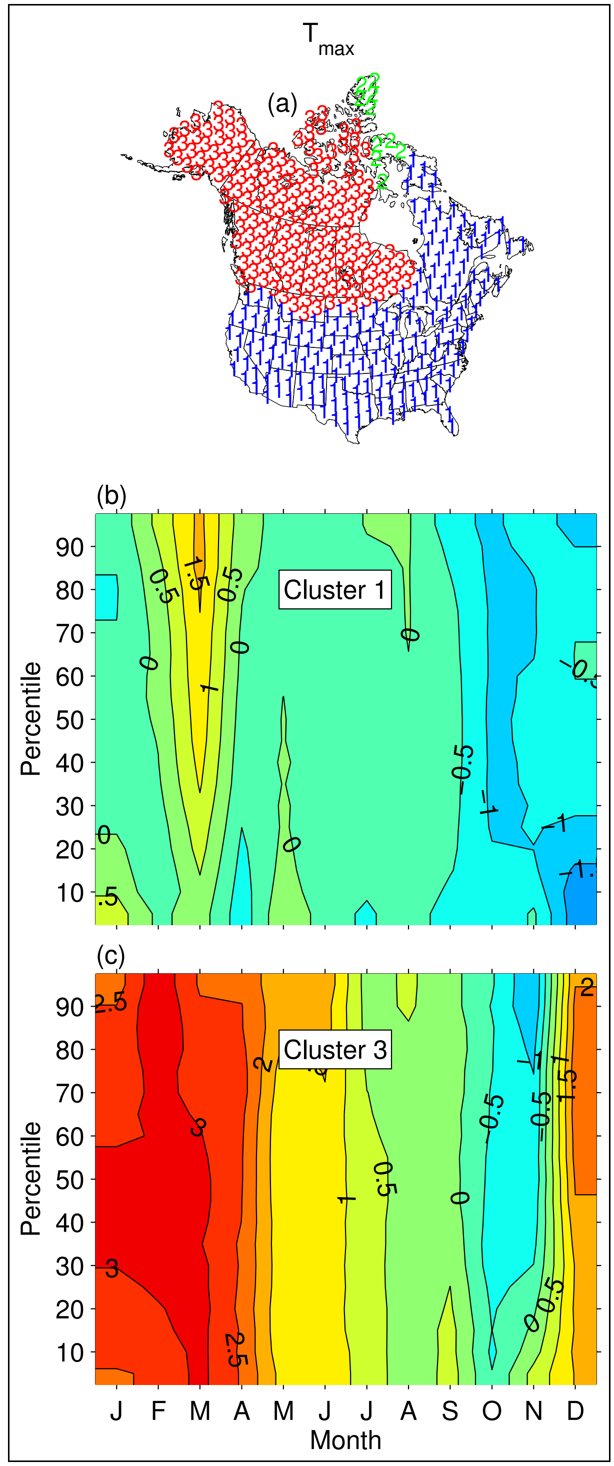

Fig. 5. Average-linkage clusters of spatially averaged trends (°C/50yr) in time-varying percentiles of T_{max} over North America from 1948 to 2000: (a) map of locations falling within the three primary clusters, (b) spatially averaged percentile trends for cluster 1, and (c) spatially averaged trends for cluster 3.

during March and moderate cooling from October through December. The pattern in Alaska and western Canada includes locations that have experienced strong warming in T_{max}, with trends exceeding 2°C/50yr for nearly all percentiles from December through April (Fig. 5c). A T_{max} pattern representing a portion of extreme northern Canada (cluster 2 in Fig. 5a) has mixed signals and represents only 3% of North American land area.

5. CONCLUSIONS

The trends in daily air-temperature percentiles reported here emphasize the importance of late winter and spring in the changing climate of North America (Bradley et al., 1999; Brown et al., 1999; Groisman et al., 1994; Keeling et al., 1996;Z hou et al., 2001). Little warming, and even cooling, has occurred during the fall season at most locations. When turning to air-temperature variations as a causal factor for biophysical changes, other researchers have nearly always sought relationships between *mean* air temperature and response variables such as CO_2 sequestration, growing-season length, snow cover, tree growth, or the timing of bird migrations (Briffa et al., 1998; Jacoby and D'Arrigo, 1995; Menzel and Fabian, 1995; White et al., 1999), sometimes with limited success. While most response variables are strongly influenced by both mean temperature and nonthermal factors, many also respond closely to trends and variability in noncentral portions of the T_{min} and T_{max} frequency distributions (Meehl et al., 2000). Growing-season length, in particular, is closely coupled with lower-tail variations in T_{min} (Robeson, 2002b). Future research on the impacts of recent climatic change should consider variations in the full range of air-temperature frequency distributions whenever high-quality daily air-temperature data are available.

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