PROBLEMS IN EVALUATING REGIONAL AND LOCAL TRENDS IN TEMPERATURE: AN EXAMPLE FROM EASTERN COLORADO, USA

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ABSTRACT

We evaluated long-term trends in average maximum and minimum temperatures, threshold temperatures, and growing season in eastern Colorado, USA, to explore the potential shortcomings of many climate-change studies that either: (1) generalize regional patterns from single stations, single seasons, or a few parameters over short duration from averaging dissimilar stations; or (2) generalize an average regional pattern from coarse-scale general circulation models. Based on 11 weather stations, some trends were weakly regionally consistent with previous studies of night-time temperature warming. Long-term (80 + years) mean minimum temperatures increased significantly ($P < 0.2$) in about half the stations in winter, spring, and autumn and six stations had significant decreases in the number of days per year with temperatures $\leq -17.8\,°C$ ($\leq 0\,°F$). However, spatial and temporal variation in the direction of change was enormous for all the other weather parameters tested, and, in the majority of tests, few stations showed significant trends (even at $P < 0.2$). In summer, four stations had significant increases and three stations had significant decreases in minimum temperatures, producing a strongly mixed regional signal. Trends in maximum temperature varied seasonally and geographically, as did trends in threshold temperature days $\geq 32.2\,°C$ ($\geq 90\,°F$) or days $\geq 37.8\,°C$ ($\geq 100\,°F$). There was evidence of a sub-regional cooling in autumn's maximum temperatures, with five stations showing significant decreasing trends. There were many geographic anomalies where neighbouring weather stations differed greatly in the magnitude of change or where they had significant and opposite trends. We conclude that sub-regional spatial and seasonal variation cannot be ignored when evaluating the direction and magnitude of climate change. It is unlikely that one or a few weather stations are representative of regional climate trends, and equally unlikely that regionally projected climate change from coarse-scale general circulation models will accurately portray trends at sub-regional scales. However, the assessment of a group of stations for consistent more qualitative trends (such as the number of days less than $-17.8\,°C$, such as we found) provides a reasonably robust procedure to evaluate climate trends and variability. Copyright © 2002 Royal Meteorological Society.

1. INTRODUCTION

Climate change can greatly affect natural and social systems at local, regional, and national scales (Watson *et al.*, 1996). For example, local farmers and ranchers are concerned about the duration of frost-free days or trends in maximum or minimum temperatures to protect crops or forage (Kittel, 1990; Schimmelpfennig

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et al.; 1996; D. Ojima, unpublished report, 1997; Quintana-Gomez, 1999). Regional managers of public lands are concerned about the ability of native plants and animals to adapt to rapidly changing climates along with other stresses such as habitat loss, invasive exotic species, air and water pollution, and altered disturbance regimes (Stohlgren, 1999). Though there are increased efforts to influence policy at national and international scales (Watson et al., 1996), many management decisions affecting climate-change policy and most mitigation efforts may be at local and regional scales. Thus, it is critically important to assess the direction and magnitude of climate change at local and regional scales. Such regional information is also vital to evaluate simulations of climate change at national and global scales (Doherty and Mearns, 1999).

There are two common problems with many climate-change studies. First, many analyses are made using single (or a few) weather stations in conjunction with small-scale experiments (e.g. Alward *et al*., 1999) or observational studies of particular natural areas (e.g. Singer *et al*., 1998, Williams *et al*., 1996). A problem arises when the authors (or the readers) generalize regional patterns from single stations, single seasons, or a few parameters over a short duration. For example, Alward *et al*. (1999) innocently described increasing minimum temperatures of 0.12 °C/year since 1970 at one weather station at the Central Plains Experiment Range (CPER) in northeastern Colorado. The journal editor requested altering the title of the paper to 'Grasslands and Global Nocturnal Warming'. Melillo (1999) used the results of the Alward *et al*. (1999) as further evidence that the Central Grasslands in the USA and the Earth were warming. Escalating the issue further, the news media report on this work sensationalized that 'Global warming could mean trouble for ranchers on the plains of Colorado and New Mexico' (Associated Press). This chain of events may not be uncommon, and few stop to ask whether neighbouring stations show similar long-term trends.

A second common problem in climate-change studies occurs when national or global-scale coverages of coarse-grained (e.g. 3.75° latitude/longitude grid interval) general circulation model (GCM) simulations are used to infer possible regional climate trends. Several co-authors of this paper confess to falling into this easy trap in proposal writing and simplifying introduction sections in popular articles. For example, Stohlgren et al. (1995) stated that 'current projections for a double-CO_2 climate in the next 50 years generally show a warming of 3–4 °C', based on GCM simulations published by Wilson and Mitchell (1987) and Houghton *et al*. (1990). More recently, as part of a national assessment of the effects of global change, the Canadian Climate Center and Hadley Centre GCMs were used to show possible scenarios for the Central Great Plains (D. Ojima, unpublished report, 1997). For all of Colorado, the models simulated a uniform increase in minimum temperatures of 5–6 °C (Canadian model) or 1–2 °C (Hadley model) from 1990 to 2090. For maximum temperatures, the Canadian model simulated increases of 5–6 °C for northeastern Colorado and 6–7 °C increases for southeastern Colorado over the next century, whereas the Hadley model simulated modest increases of 2–3 °C uniformly over most of the ten-state region.

We feel that many regional climate studies routinely ignore or downplay key limitations of GCM's, such as poor topographic resolution and limited biological feedbacks in the models (Pielke *et al*., 1998), ignoring differences in land use and changes over time as a major driving variable (Pielke *et al*., 1998; Stohlgren *et al*.; 1998, Chase *et al*., 1999), and having an extremely poor ability to replicate historic climate trends at regional and local scales (Doherty and Mearns, 1999). In the quest for generalized trends in climate change (e.g. Watson *et al*., 1996, many others), few scientists appear to be asking if coarse-grid climate simulations can accurately describe regional (much less local) climate patterns. However, our primary concern is that poor-resolution climate models continue to produce greatly smoothed or 'averaged' results over fairly broad regions, and that these average conditions may mask important local anomalies in the magnitude or direction of climate change.

These two problems may not be severe if spatial variation in climate is minimal. However, if several climate stations in a relatively homogeneous landscape do not behave similarly for several weather parameters, then extrapolating regional trends from single (or a few) sites, or generalizing regional trends from coarse-scale climate models will not be correct. Our objective was to evaluate the long-term trends of several weather parameters for 11 weather stations in the eastern Colorado plains. Specifically, we address the direction, magnitude, and statistical significance of trends in various parameters with respect to season of year, regional consistency, and differences among neighbouring stations.

2. DATA

Eleven long-term weather stations in eastern Colorado were selected for this study based on location, length and completeness of record, and observational consistency. Most of these sites are part of the US Cooperative Network. The primary goal for site selection was to represent, as well as possible and as long as possible, a variety of geographic areas of the Central Great Plains, including grasslands, non-irrigated cultivated regions, and areas with extensive irrigated agriculture. Rural areas are predominant, but urbanized areas were also included in the list. Station selection was made utilizing station data and station history documentation on file at the Colorado Climate Center.

The 11 sites selected are listed in Table I and their locations are shown in Figure 2. The station elevations ranged from 1033 to 1638 m (Table II). Nine sites were predominantly rural, with surrounding areas of rangeland, pastures, or cropland, and with historically low populations less than 10 000. Fort Collins was the only major urban site, with a population close to 100 000. Five sites are in northeastern Colorado, and six sites are found in the Arkansas River basin in southeastern Colorado. By no means are these the only long-term climate monitoring stations, but they appeared to be among the best available in terms of completeness of record and the fewest station changes and potential inhomogeneities. Of these 11 sites, nine are on the list of US Historical Climate Network (USHCN) stations. Akron 4E and the Long Term Ecological Research site at the CPER northeast of Fort Collins were not.

USHCN station data have been the focus of many studies of regional and national climate variations and trends. The cooperative weather observations that make up the vast majority of the USHCN are the most consistent source of century-long climatic data time series available in the USA (NRC, 1998). Nevertheless, several sources of potential data inhomogeneities have been found that are inherent to this network. Inhomogeneities have been documented associated with changing the time when the once-daily cooperative observations are taken. Inevitable changes in observers and associated station relocations have been found to introduce data inhomogeneities. Changes in instrumentation can result in discontinuities. Finally, urbanization in the vicinity of a weather station has been shown to introduce gradual temperature changes that are a local effect.

Efforts have been made since the 1980s to identify objectively and adjust for inhomogeneities in long-term data in order to produce data sets capable of detecting long-term climate trends. Easterling *et al.* (1996) summarize the procedure used by the USHCN to provide a more consistent record of long-term monthly mean weather data. These steps, in order, are:

1. a hand-checked quality assurance of data outliers from the original records;
2. time-of-observation biases are adjusted for (Karl *et al.*, 1986);
3. an adjustment based on the introduction of the maximum–minimum temperature system (MMTS) using the bias value given in Quayle *et al.* (1991);

Table I. 1910–90 population census data (source: 13th–21st US Census)

Year	Akron	Cheyenne Wells	CPER (Ault)	Eads	Fort Collins	Fort Morgan	Holly	Lamar	Las Animas	Rocky Ford	Wray
1910	647	270	569	125	8210	2800	724	2977	2008	3230	1000
1920	1401	540	769	406	8755	3818	1500	2512	2252	3746	1538
1930	1135	1348	931	1123	11 489	4423	1107	4233	2517	3426	1785
1940	1417	695	761	700	12 251	4884	864	4445	3232	3494	2061
1950	1605	1154	866	1015	14 937	5315	1236	6829	3223	4087	2198
1960	1890	1020	799	929	25 027	7379	1108	7369	3402	4929	2082
1970	1775	982	841	795	43 337	7594	993	7797	3148	4859	1953
1980	1716	950	1056	878	65 092	8768	969	7713	2918	4804	2131
1990	1588	1128	1107	787	87 758	9068	868	8343	2362	4162	1998

Table II. Weather station histories and site descriptions

Station name/number	Lat/lon	Elevation (m)	Population (1990)	Years of data used	Data record available (%)	Site description	Station location changes	Predominant time of observation
Akron 4E/50109	40° 09′/ 103° 09′	1384	1588	1912–98 (87)	100	Rural, open field, fenced area with native grasses, flat to gently sloping	1	Consistent, AM
Cheyenne Wells/51564	38° 49′/ 102° 21′	1295	1128	1910–98 (89)	97.3	Rural, farm and pasture land, gently sloping, few trees or shrubs	4	Consistent, early evening
CPER/NA	40° 48′/ 104° 45′	1638	1107	1948–98 (51)	99.6	Rural, native grasses, rangeland	N/A	N/A
Eads/52446	38° 29′/ 102° 46′	1298	787	1925–98 (74)	92.8	In town, grassy lawn, some buildings in the vicinity	4	Evening before 1982, 11AM 1982–87, 7AM since 1987
Fort Collins/53005	40° 35′/ 105° 05′	1524	87 758	1910–98 (89)	100	Urban, CSU Campus, gently sloping grass lawn	3	Consistent 7PM
Fort Morgan/53038	40° 15′/ 103° 48′	1317	9068	1948–98 (51)	98.9	Edge of town in broad agricultural valley close to sugar factory	1	5PM through 1916, 7AM or 8AM 1917–present
Holly/54076	38° 03′/ 102° 07′	1033	868	1918–98 (81)	93.1	Small town — open site with flat pastures and irrigated farmland nearby	4	PM through 1920, AM 1920–26, PM 1926–58, AM 1958–present
Lamar/54770	38° 04′/ 102° 37′	1109	8343	1910–98 (89)	98.0	Open residential in gently sloping agricultural valley	4	5PM through 1936, 12AM 1936–87, 7AM 1987–present
Las Animas/54834	38° 05′/ 103° 13′	1186	2362	1910–98 (88)[a]	96.4	In town, nearly flat, on gravel substrate, mostly treeless, close buildings	3	PM to 1912, AM 1913–26, 5PM 1926–88, 12AM 1989–present
Rocky Ford 2SE/57167	38° 02′/ 103° 42′	1271	4162	1910–98 (89)	99.6	Rural, flat, irrigated farmland, farm buildings nearby	0	Consistent 5PM
Wray/59243	40° 04′/ 102° 13′	1070	1998	1918–97 (79)[b]	91.3	Rural, with sloping river valley	5–7	PM through 1987, AM 1987–present

[a] missing 1928.
[b] missing 1986.

4. an adjustment based on station moves using the procedure described in Karl and Williams (1987); and
5. an adjustment for urban effects as described in Karl *et al.* (1988). Recent papers to evaluate the urban temperature bias include Gallo and Owen (1999), and Owen *et al.* (1998a,b).

We could have simply used USHCN adjusted data for the nine sites. However, our familiarity with these data and adjustment procedures caused us to proceed with caution. We began by examining unadjusted 'raw' data for our 11 sites, independently identifying changes in observation time, changes in instrumentation and changes in station location. We also examined missing data and some of the USHCN estimates. We found several unresolved inconsistencies. For example, MMTS adjustments were applied to eight of the 11 stations. However, only six of these sites use the MMTS for official temperature records. As of 1999, Akron 4E, Cheyenne Wells, Fort Collins, and Rocky Ford weather stations continue to use traditional glass thermometers. Eads, Fort Morgan, Holly, Lamar, Las Animas and Wray stations changed from traditional glass to electronic thermometers in the middle to late 1980s.

The Colorado Climate Center has conducted its own test of the comparison of the National Weather Service MMTS with the traditional liquid-in-glass thermometers. The conclusions of Doesken and McKee (1995) were that the MMTS read about 0.5 °C cooler in the daily maximum temperatures but no change in minimum temperatures were noted annually, although a slight annual cycle in minimum temperature differences was noted. These findings were based on 10 years of side-by-side comparison at one Colorado station. Unpublished comparisons at other stations in Colorado found widely varying results that differed even more from the National Climatic Data Center (NCDC) results. In the mean of many stations over broad areas, the conclusions of Quayle *et al.* (1991) and the subsequent procedure for adjusting temperature time series to accommodate the change from liquid-in-glass thermometers may be appropriate. But, at any given station, a single adjustment factor may not be appropriate, and we therefore did not apply the MMTS adjustment to any of the six stations now using the MMTS.

The urban adjustment was not much of a factor in this study, since most of the sites are rural or come from small towns that have not had significant population growth. The Fort Collins station, which has seen a population growth from around 10 000 to over 100 000 during the 20th century was affected (Table I). Applying the USHCN adjustment for urbanization to the Fort Collins data resulted in warming temperatures early in the period of record with respect to recent years. This general adjustment is appropriate and was applied. Fort Collins clearly has experienced localized warming accentuated by urbanization (Doesken, 2000). However, the actual adjustment is more variable and irregular than a simple population-based linear model suggests.

The time of observation biases clearly are a problem in using raw data from the US Cooperative stations. Six stations used in this study have had documented changes in times of observation. Some stations, like Holly, have had numerous changes. Some of the largest impacts on monthly and seasonal temperature time series anywhere in the country are found in the Central Great Plains as a result of relatively frequent dramatic interdiurnal temperature changes. Time of observation adjustments are therefore essential prior to comparing long-term trends.

We attempted to apply the time of observation adjustments using the paper by Karl *et al.* (1986). The actual implementation of this procedure is very difficult, so, after several discussions with NCDC personnel familiar with the procedure, we chose instead to use the USHCN database to extract the time of observation adjustments applied by NCDC. We explored the time of observation bias and the impact on our results by taking the USHCN adjusted temperature data for 3 month seasons, and subtracted the seasonal means computed from the station data adjusted for all except time of observation changes in order to determine the magnitude of that adjustment. An example is shown here for Holly, Colorado (Figure 1), which had more changes than any other site used in the study.

What you would expect to see is a series of step function changes associated with known dates of time of observation changes. However, what you actually see is a combination of step changes and other variability, the causes of which are not all obvious. It appeared to us that editing procedures and procedures for estimating values for missing months resulted in computed monthly temperatures in the USHCN differing from what a user would compute for that same station from averaging the raw data from the Summary of the Day

Holly Fall Max Magnitudes

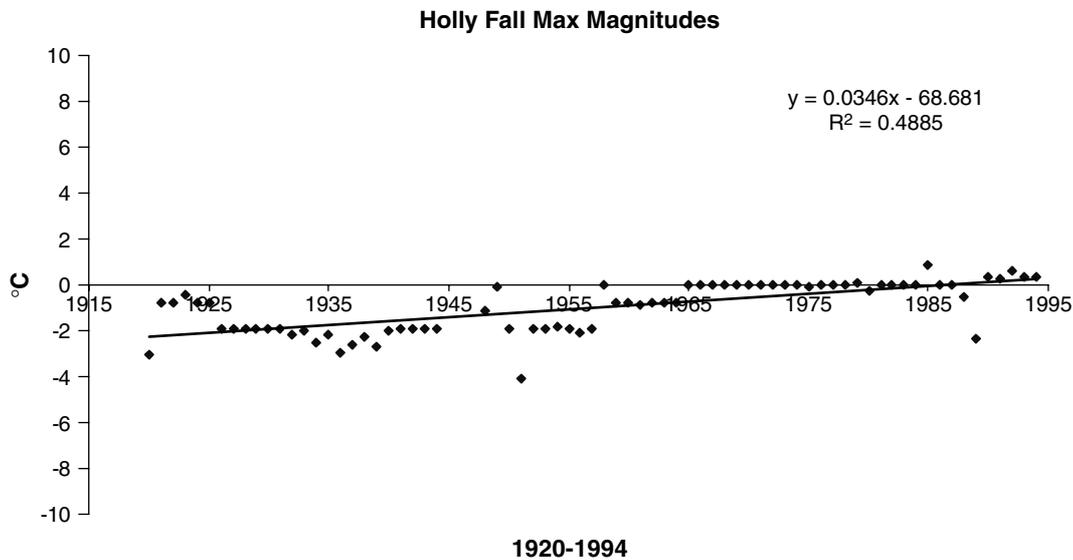$$y = 0.0346x - 68.681$$
$$R^2 = 0.4885$$

Figure 1. 'Time of observation' adjustment for the 3 month autumn season for the Holly, Colorado, station deduced by subtracting USHCN raw data from adjusted values (USHCN data was available only through 1994)

Cooperative Data Set. This simply points out that when manipulating and attempting to homogenize large data sets, changes can be made in an effort to improve the quality of the data set that may or may not actually accomplish the initial goal.

Overall, the impact of applying time of observation adjustment at Holly was to cool the data for the 1926–58 with respect to earlier and later periods. The magnitude of this adjustment of 2 °C is obviously very large, but it is consistent with changing from predominantly late afternoon observation times early in the record to early morning observation times in recent years in the part of the country where time of observation has the greatest effect. Time of observation adjustments were also applied at five other sites.

Examples of adjustments that are not considered in the USHCN are other types of non-urban short- and long-term landscape changes. Lewis (1998), for example, has found about a 1 °C annual average increase in ground surface temperature at two closely spaced locations in western Canada when a site is locally cleared of forest. O'Brien (1998) found decreases in the average daily maximum temperature and temperature range when locations in southern Mexico were deforested.

For eastern Colorado, Segal *et al.* (1988) used geostationary satellite observations of surface irradiance temperature, special radiosonde soundings, and aircraft cross-sections to document significantly cooler and higher humidity air near the ground associated with irrigated crops. Satellite images from the EROS Data Center (http://edcwww.cr.usgs.gov/) illustrated large spatial and temporal variations of transpiring vegetation in eastern Colorado during the growing season. Over the western USA, Schwartzman *et al.* (1998) document a slight upward trend in regional average dew point temperatures that could be associated with agricultural conditions. Robinson (2000) also found an increase of dew point temperatures over most of the counterminous USA in the spring and summer. Durre *et al.* (2000) found that the frequency of record and near-record high temperatures in the summer are sensitive to antecedent soil moisture.

When comparing trends in time series between stations, it is important that record lengths be identical or at least as similar as possible. Of the 11 sites selected, most have data records back to 1910 or earlier. However, computations of trends were limited to the period 1918 to 1998 to assure comparability. Data at Eads only began in 1925, so some minor differences could result. Data for the CPER site are only available since 1948. This 30 year difference in period of record is very significant and could limit the comparability of its results with the other stations.

To summarize our approach to evaluating data homogeneity, we did not apply objective numerical techniques for homogeneity testing. Instead, we selected the best long-term stations and only applied

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adjustments that were clearly warranted, i.e. time of observation adjustments at six stations and an urbanization adjustment at one station. MMTS adjustments were not applied. The record of station moves was examined for each station, but no station move adjustments were estimated. Remarkably, five of these stations had no appreciable station moves documented since 1910, and discontinuities were not apparent in station-to-station comparisons in most cases.

We have concluded, by a detailed examination of the data at each site, that the application of some adjustments proposed to remove inhomogeneities (MMTS, station moves) does not decrease the heterogeneity of the data at an individual site and may introduce additional uncertainties. Therefore, we have elected to work only with data individually quality checked by the Colorado Climate Center. Non-climatic inhomogeneities are likely to remain, but where stations are widely spaced, as they are in eastern Colorado, and changes in vegetation and land use continue, true homogeneity can never be achieved. Introducing systematic adjustment procedures where discontinuities are not systematic will not solve the problem. It may be appropriate for regional studies, but it is a problem for comparing individual stations.

Using this data, seasonal variation in average minimum and maximum temperatures was assessed in 3 month 'seasons': winter (December–February), spring (March–May), summer (June–August), and autumn (September–November). To assess trends in threshold temperature events, we counted the number of days each year that were $< -17.8\,°C$ ($<0\,°F$), $<0\,°C$ ($<32\,°F$), $>32.2\,°C$ ($>90\,°F$), and $>37.8\,°C$ ($>100\,°F$) for each station, and assessed for regional patterns.

For all linear regressions, $P < 0.2$ was used to test significance. This was a conservative way to show agreement (i.e. significant trends versus non-significant trends) among stations and to avoid the Type II error (Zar, 1984). We did not want to 'reject' a temperature trend where one might weakly exist.

3. RESULTS

3.1. Seasonal variation in average minimum and maximum temperatures

We found fairly consistent results in average minimum temperature, with about half the sites showing increasing trends in most or all seasons (Table III). Fort Collins, Fort Morgan, and Las Animas, representing sites with high to low human populations, each had increases in minimum temperature across all seasons. However, during the summer (i.e. the warmest part of the year and a major part of the growing season), three stations had significant cooling trends in minimum temperature. Of these, Holly also had significant decreases in minimum temperature in the summer and autumn. Thus, the direction of change was not always consistent across the region.

The magnitude of temperature change, however, was inconsistent across sites and seasonally. Slopes (on a 100 year time frame) ranged from $-0.06\,°C/100$ years at Holly (low human population) to $+3.6\,°C/100$ years in Fort Collins (high human population) for average minimum temperatures in winter. For average minimum temperatures in summer, slopes ranged from $-2.1\,°C/100$ years at Holly to $+2.4\,°C/100$ years in Fort Collins. Of the 44 regression tests conducted in this analysis (11 sites × 4 seasons), 19 showed no significant trends, 21 showed significant ($P < 0.2$) increases in average minimum temperature, and four tests showed significant decreases in temperature.

Long-term trends in average maximum temperature were mixed (Table IV). Only one station, Rocky Ford, had increases in maximum temperature across all seasons, although Fort Collins showed significant increases in three of four seasons. However, Lamar had significant long-term decreases in maximum temperature in all seasons, and five sites had decreasing trends in the summer and autumn. Las Animas, which had significant increases in minimum temperatures in autumn (Table III), unexpectedly had significant decreases in maximum temperature (Table IV). The CPER, which had significant increases in minimum temperatures in the spring and winter (Table III), also had significant decreases in maximum temperature in summer, autumn and winter (Table IV). Thus, the direction of change was not always consistent across the region, nor between minimum and maximum temperatures.

Table III. Of the 11 stations, these have significant ($P < 0.2$) increasing or decreasing average minimum temperatures and magnitude of change in °C/100 years

Season	Years of record	Increasing minimum temperature			Years of record	Decreasing minimum temperature		
		Station	°C/100 years	$P<$		Station	°C/100 years	$P<$
Spring	87	Akron 4E	0.6	0.2				
	89	Cheyenne Wells	1.2	0.05				
	51	CPER	3.9	0.01				
	89	Ft Collins	3.6	0.001				
	50	Ft Morgan	3.1	0.001				
	88	Las Animas	2.8	0.001				
Summer	89	Ft Collins	2.4	0.001	72	Eads	−1.1	0.2
	51	Ft Morgan	2.1	0.01	79	Holly	−2.1	0.005
	88	Las Animas	2.2	0.002	89	Rocky Ford	−0.4	0.2
	77	Wray	1.3	0.05				
Autumn	87	Akron 4E	0.6	0.2	77	Holly	−1.4	0.1
	89	Ft Collins	2.4	0.001				
	51	Ft Morgan	2.2	0.2				
	88	Las Animas	2.2	0.01				
	77	Wray	1.7	0.2				
Winter	87	Akron 4E	1.4	0.05				
	89	Cheyenne Wells	1.4	0.02				
	51	CPER	4.4	0.01				
	89	Ft Collins	3.6	0.001				
	51	Ft Morgan	2.3	0.2				
	88	Las Animas	2.8	0.001				

3.2. Trends in threshold temperature events

Trends in threshold temperature events also showed very mixed signals (Table V). Six sites had significantly fewer days <-17.8 °C, while five sites had significantly fewer days ≤ 0 °C (four sites were in common). Three sites had significantly fewer days ≥ 32.2 °C, while four sites had significantly more days >37.8 °C. Only Lamar had significantly fewer days ≥ 37.8 °C. The CPER site had fewer days ≤ -17.8 °C and ≤ 0 °C, while also having fewer days ≥ 32.2 °C, indicating less-extreme temperatures over time. Holly has seen more threshold temperatures altogether, with increased days ≤ 0 °C and more days ≥ 32.2 °C.

The magnitude of the trends in threshold events was not great. Only Fort Collins had trends >5 days/100 years <-17.8 °C and <0 °C. Only Lamar had >5 days/100 years ≥ 32.2 °C and ≥ 37.8 °C. And, only Fort Morgan had >5 days/100 years ≥ 32.2 °C and ≥ 37.8 °C. The majority of sites showed no significant trends in threshold temperature events (Table V).

3.3. Growing-season length

The growing season is obviously of important societal relevance. In computing the lengths of the growing season from the data, we did not make any adjustments to the original data; since growing-season length is not expected to be significantly dependent on any of the homogenization procedures.

The length of the climate record had a significant effect on calculating the change in the number of growing season days in the study region (Table VI). When a 27 year record is used (1970–96, with some missing data), eight stations showed positive gains in the frost-free period over time (Table VI). Values were projected over 100 years to standardize for missing data and to compare the slopes of the trends with a longer-term record (see below). Over this recent time period, the estimated change in growing-season days ranged from −3.4 days/100 years at Akron to 8.4 days/100 years at the CPER. With a longer-term record (1940–96),

Table IV. Of the 11 stations, these have significant ($P < 0.2$) increasing or decreasing average maximum temperatures and magnitude of change °C/100 years

Season	Years of record	Increasing maximum temperature			Years of record	Decreasing maximum temperature		
		Station	°C/100 years	$P <$		Station	°C/100 years	$P <$
Spring	87	Akron 4E	1.3	0.1	88	Lamar	−1.5	0.1
	89	Ft Collins	1.7	0.05				
	50	Ft Morgan	3.3	0.05				
	88	Rocky Ford	2.7	0.001				
Summer	89	Ft Collins	0.9	0.05	51	CPER	−2.8	0.1
	89	Rocky Ford	1.3	0.05	72	Eads	−1.4	0.2
					89	Lamar	−2.1	0.001
Autumn	87	Rocky Ford	1.3	0.05	51	CPER	−6.8	0.001
	77	Wray	2.9	0.1	73	Eads	−2.4	0.05
					77	Holly	−3.1	0.002
					89	Lamar	−3.1	0.005
					88	Las Animas	−1.6	0.2
Winter	87	Akron 4E	2.2	0.02	51	CPER	−4.3	0.05
	89	Cheyenne Wells	1.1	0.2	79	Holly	−1.7	0.1
	89	Ft Collins	1.7	0.05	73	Eads	−1.6	0.2
	89	Rocky Ford	1.8	0.05	51	Ft Morgan	−0.4	0.1
	79	Wray	2.2	0.2	89	Lamar	−1.4	0.2

Table V. Stations with trends in number of days passing selected temperature thresholds. Number of years of record are in parentheses. A bullet identifies the sites with trends that are equal or greater than 5 days per century. Locations that had substantial population growth during the period of record are identified with an asterisk

Fewer days	More days	Fewer days	More days
$T_{min} \leq -17.8$ °C		$T_{min} \leq 0$ °C	
• Akron 4E (87)		• Akron 4E (87)	• Holly (79)
• CPER (51)		• CPER (51)	
• Ft Collins (89)*		• Ft Collins (89)*	
• Las Animas (81)		• Las Animas (79)	
• Rocky Ford (89)		• Wray (64)	
Cheyenne Wells (89)			
$T_{max} \geq 32.2$ °C		$T_{max} \geq 37.8$ °C	
• CPER (51)	• Akron 4E (87)	• Lamar (89)*	• Ft Morgan (39)*
• Eads (62)	• Ft Collins (89)*		• Holly (79)
• Lamar (88)*	• Ft Morgan (51)*		• Rocky Ford (89)
	• Rocky Ford (89)		

three of 11 stations had reversed their trends. Rocky Ford, for example, changed from +4.0 days/100 years based on the short-term record to −4.4 days/100 years based on the long-term record. Interestingly, the two stations with decreasing growing season length 1940–96 (Akron 4E and Rocky Ford 2SE) were stations that have been free of discontinuities in time of observation, station location and urbanization.

Given high interannual and decadal variability in climate, it is obvious that short-term climate records can be misleading in evaluating trends. The growing-season data shown here (Table VI) clearly demonstrate reversal of trends. Furthermore, besides the three stations where reversals of trends did not appear,

Table VI. Trends in number of growing-season days per 100 years for weather stations in eastern
Colorado projected from $n \neq$ years of data. Values of n less than the period of record indicate data
for one or more years were missing

Station	Based on 1970–96 data			Based on 1940–96 data		
	Days/100 years	$P <$	n	Days/100 years	$P <$	n
Akron 4E	−3.4	0.5	27	−3.0	0.5	57
Cheyenne Wells	2.1	0.5	20	1.2	0.5	40
CPER	8.4	0.1	27	7.5	0.001	57
Eads 2S	−2.0	0.5	15	8.2	0.5	41
Fort Collins	4.7	0.5	27	4.2	0.002	57
Fort Morgan	5.1	0.2	22	6.7	0.5	43
Holly	4.4	0.5	24	1.1	0.5	41
Lamar	−2.5	0.5	24	9.2	0.5	51
Las Animas	4.8	0.2	21	2.4	0.2	45
Rocky Ford 2SE	4.0	0.5	26	−4.2	0.5	56
Wray	3.9	0.5	17	3.7	0.05	37

seven of the remaining eight stations had exaggerated trends using the short-term analysis periods
(Table VI).

3.4. Geographic anomalies

Geographic anomalies abound in the data set, where neighbouring sites have significant and opposite trends
or where they differ substantially in the magnitude of change (Figure 2). For example, winter maximum
temperatures decreased at a rate of 2.2 °C/100 years at Lamar, but only decreased 0.2 °C/100 years at Las
Animas just 60 km away. Winter minimum temperatures increased at a rate of 2.8 °C/100 years at Las Animas,
but only increased 0.3 °C/100 years at Rocky Ford just 43 km away. (Las Animas is a small town, but with
a very urban-type of station exposure, which could explain its relative warmth.)

4. DISCUSSION

4.1. Local versus regional and global climate change

Only one regional trend in climate change was detected: there was evidence of a large-scale pattern of
night-time temperature warming consistent with theories of climate warming associated with the radiative
effect of increased carbon dioxide (Allard *et al.*, 1999; Melillo, 1999). However, there were seasonal and
site-specific exceptions to this trend (Table III). Furthermore, spatial and temporal variation in the magnitude
and direction of change was enormous for all the other temperature parameters tested, and, in the majority
of tests, few stations showed significant trends (even at $P < 0.2$; Tables III–VI, Figure 2). From the summer
data, we were compelled to ask how four stations could have significant increases and three stations have
significant decreases in minimum temperatures. How can one station (Holly) have significantly more days
below freezing, while neighbouring sites have significantly fewer days below freezing? These results strongly
suggest that regional trends can be seasonally variable, and local forcing from land-use change (Stohlgren
et al., 1998; Chase *et al.*, 1999), and other highly localized unknown causes, can override regional and global
forcing.

Ecologically, plants and animals may be more restricted by temperature extremes than average temperature
(Begon *et al.*, 1990). Likewise, the agriculture and livestock industries in eastern Colorado are strongly
affected by extremes in temperature and the length of the growing season (Duncan *et al.*, 1995). Given the
potential importance of threshold temperature events, it is difficult to imagine the societal value if there had

Geographic Anomalies

Ft. Collins and CPER, at 40 km apart, had significant and opposite trends in the number of days >=32.2'C, and in summer maximum temperatures.

CPER increased the frost-free period by 43 days between 1940 and 1996, while Akron, just 175 km away, had a decrease in 2 frost-free days over the same period.

Ft.Morgan and Akron, 56 km apart, had significant and opposite trends in winter maximum temperatures.

Wray and Akron, just 87 km apart, also had opposite trends in growing season days.

Eads and Cheyenne Wells, 52 km apart, had significant and opposite trends in winter maximum temperatures.

Eads and Las Animas, 60 km apart, had significant and opposite trends in summer minimum temperatures.

Lamar and Holly, only 43 km apart, had significant and opposite trends in the number of days >=37.8'C.

Las Animas and Holly, 102 km apart, had significant and opposite trends in autumn minimum temperatures.

Although only about 43 km apart, Rocky Ford and Las Animas had significant and opposite trends in maximum temperature in autumn, and in minimum temperatures in summer. Rocky Ford had a decrease in frost-free period of 2 days between 1940 and 1996, while Las Animas had an increase in the growing season by 20 days.

Rocky Ford and Lamar, 100 km apart, had significant and opposite trends in the number of days <= -17.8'C. Rocky Ford and Lamar also had opposite trends in the growing season days.

CPER, Ft. Collins, Ft. Morgan, Akron, Wray, Cheyenne Wells, Eads, Las Animas, Rocky Ford, Lamar, Holly
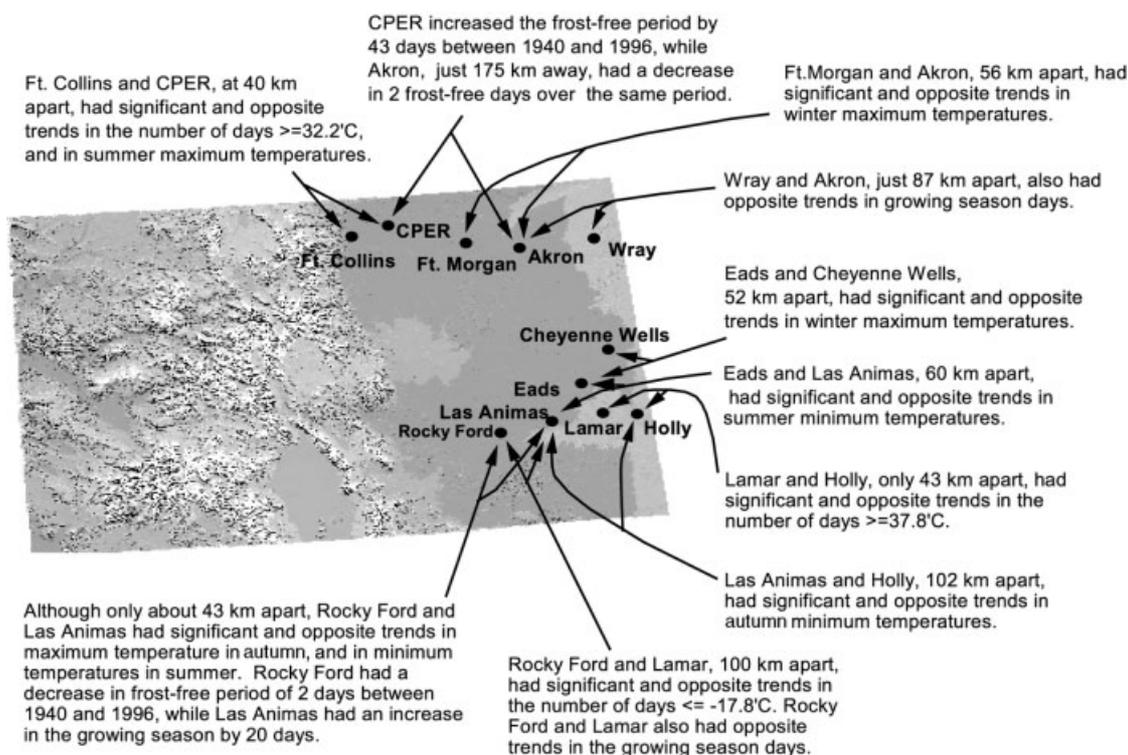
Figure 2. Geographic anomalies in temperature trends in eastern Colorado

been a claim in 1900 that average minimum temperatures in the region would warm by up to 1 °C by the year 2000, a claim that fits the eastern Colorado average fairly well (Table IV). There was little indication of such consistent trends in maximum temperature in our study region, due in part to large seasonal (Tables III and IV) and spatial variability (Tables III–VI; Figure 2). Five stations had significant increases in winter maximum daily temperature, and five stations had significant decreases (with no obvious geographic pattern). There was evidence of a sub-regional cooling in autumn maximum temperatures, as five stations had significant decreasing trends, whereas only two stations had significant increasing trends. These results are consistent with a growing body of literature suggesting that local- and regional-scale irrigated agriculture can have a summer and early autumn cooling effect on climate for the region (Segal *et al.*, 1988, 1989) and over adjacent regions (Stohlgren *et al.*, 1998; Chase *et al.*, 1999). Local variation made it difficult to portray a regional trend in most climate parameters, and thus the simple climate projection from a century ago of a regional temperature trend would not have been of much value at a local level.

There were, for example, no consistent trends in threshold hot temperatures across the region (Table V). Two stations 43 km apart (Lamar and Holly) had significant trends in opposite directions for days with maximum $T \geq 37.8$ °C. Likewise, several sets of stations <60 km apart had opposite significant trends in days ≥ 32.2 °C, winter (or summer) maximum temperatures, or minimum summer temperatures (Figure 2). Stations also varied in the magnitude of change. Fort Collins, a rapidly urbanizing site, warmed by 4.8 °C in minimum temperature from 1948 to 1998 (using original, unadjusted data), three times as great as the average slopes of the other sites. In the relatively homogeneous terrain of eastern Colorado, long-term weather trends in both temperature and threshold events showed very mixed signals in the direction, magnitude, and statistical significance of climate change. Kittel (1990) also found inconsistencies in the records of neighbouring stations in northeast Colorado. Again, spatial and temporal variation cannot be ignored when evaluating the direction and magnitude of climate change (Figure 2).

4.2. Inconsistencies in the responses of multiple temperature parameters

There was little indication that various temperature parameters tracked each other well at regional or local scales. Significant trends in minimum and maximum temperatures appeared decoupled for most stations. In the summer, for example, Rocky Ford had significantly decreasing minimum temperatures and significantly increasing maximum temperatures (Tables III and IV). In contrast, in the winter, the CPER site had significantly increasing minimum temperatures and significantly decreasing maximum temperatures. Stations with significantly fewer cold days rarely had significantly more very hot days. Only one of six sites with significantly fewer days $\leq -17.8\,°C$ (Rocky Ford) also had significantly more days $\geq 37.8\,°C$, and one site (Holly) had both more days $<0\,°C$ and more days $\geq 37.8\,°C$ (Table V).

Temperature trends that were more uniform in the winter were far less so in the summer and autumn (Tables III and IV). That is, there was also a strong disconnect seasonally, with very few sites showing consistent trends for all seasons; the summer season was the least consistent in minimum and maximum temperatures across the region. This could be unsettling for the agriculture and livestock industry, where decreasing growing season, and minimum and maximum temperatures, at some sites may reduce productivity, while increasing minimum temperatures at other sites may facilitate less desirable invasive plant species (Alward *et al.*, 1999). Unfortunately, temperature trends in the summer growing season were not unidirectional (e.g. rising minimum temperatures; Table III) and spatial variation in temperatures defies simple explanations and predictions (Figure 2).

There were also discrepancies between average minimum temperatures and the length of the growing season (number of frost-free days). For example, Akron had a significant increase in minimum spring temperatures (Table III) and had fewer days per year $\leq 0\,°C$ (Table V), but the site had a decreasing trend in the growing-season length (Table VI).

These examples point to a strong probability that different forcing mechanisms operate on different parameters at different scales. Monitoring or predicting changes in average temperatures may not provide insights on temperature thresholds and *vice versa*. High spatial and temporal variation may mask all but the most severe regional trends (Figure 2), and most sites within the region may not show the trend at all.

4.3. No one site (in this study) is 'typical' of the region

Spatial and temporal variations are enormous and they cannot be ignored. Given the spatial variation in the magnitude and direction of change for the parameters tested (Tables III–VI), and highlighted by the geographical anomalies of neighbouring sites (Figure 2), we believe that no one site evaluated in this study is 'typical' of the region. The alarming trend in minimum temperature of $0.12\,°C$/year reported by Alward *et al.* (1999) for CPER since 1970 was four times higher than the average of the other ten stations used in this study over the same period ($0.03\,°C$/year) and 12 times higher than the long-term (80+ years) average rate ($0.01\,°C$/year). The site was also atypical in trends in summer temperatures and growing-season days. Extrapolation of results from one site to another site, or from one site to the region, would be highly suspect. It may be that clusters of weather stations in other regions behave reasonably the same for most parameters and over all time periods, but our results suggest otherwise.

Climate researchers working at one or a few sites must clearly state the limitations of the data for extrapolation, including the high probability that some portion of the climate data may be a geographic anomaly (Figure 2), as well as understand sources of incongruity in single-station records (e.g. changes in station location, instrumentation, and local environment). Prudent researchers wishing to make regional extrapolations, or simply wishing to measure how typical or representative their primary study site is, may want to increase greatly the number of stations examined. Readers and users of single-site studies are likewise cautioned about extrapolating results from one site to the region and larger domains.

4.4. Models projecting average regional results may not describe any one site well, much less the region

Climate modellers have a more formidable task. It is clear for eastern Colorado that 'averaged' or 'regionally smoothed' climate scenarios are unlikely to describe specific sites well. The magnitude of spatial variation

in this relatively homogeneous region far exceeds the 'main effect' of any average projected climate change. For example, the regional, seasonally averaged change in maximum temperature over the past 80+ years was $-0.2\,°C$ for these 11 stations in eastern Colorado, whereas minimum temperatures rose $1.0\,°C$. However, trends for individual sites within eastern Colorado ranged from $-3.8\,°C/100$ years at the CPER to $+1.8\,°C/100$ years at Rocky Ford in maximum temperatures, and from $-1.1\,°C/100$ years at Holly to $+3.0\,°C/100$ years at Fort Collins in minimum temperatures.

The fact that there is so little agreement between the modelled historic record and observed temperature records at the regional level (Doherty and Mearns, 1999) may be due to the magnitude of spatial variation. Discrepancies commonly ran 3 to $9\,°C$ comparing observed and simulated values regionally smoothed from a grid width of $0.5°$ interpolated to a $2°$ grid. Temperature increases in rapidly urbanizing Fort Collins were typically three times higher than in rural sites (Table III), exaggerating the regional trend (Gallo and Owen 1998, Gallo *et al.*, 1999). Likewise, local land-use effects from irrigated agriculture have been linked to a cooling effect in the summer (Stohlgren *et al.*, 1998, Chase *et al.*, 1999). Present GCMs lack the ability to simulate the complex climate patterns and anomalies in the simple topography but heterogeneous landscape of eastern Colorado. We propose that whenever GCM simulations are used for regional purposes, the results must be presented with some estimate of spatial accuracy of results, some comparison with historic data, and some level of uncertainty clearly presented, or they will be of limited use in making management and policy decisions at local and regional scales.

The public and the media should be more sceptical about long-term climate projections for local and regional use. Simple averaged projections of average temperature change from 100 years ago until today would not have adequately described changing temperatures in eastern Colorado. Sadly, even the best climate projections of today for 100 years from now will likely suffer a similar fate.

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