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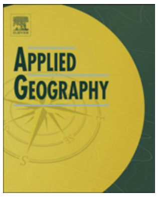

# Did irrigation impact 20th century air temperature in the High Plains aquifer region?

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## ABSTRACT

This study investigates potential impacts of widespread adoption of irrigation on long-term temperatures over the High Plains aquifer (HPA) region of the Great Plains. It is well known that availability of soil moisture can modify near surface energy partitioning (latent vs. sensible) and temperature. This study provides an assessment of the changes in the historical near surface temperature records in the HPA region due to adoption of irrigation. Long-term growing season mean monthly maximum and minimum air temperature data from 24 irrigated and 26 non-irrigated sites were analyzed. These stations are part of the US Historical Climate Network (USHCN). This study reports that growing season mean maximum temperature ($GT_{max}$) at irrigated areas is predominantly cooler than non-irrigated areas with up to 1.01 °C cooling at some locations. A geographical variation in magnitude of this cooling is also observed. The majority of irrigated locations report warming in $GT_{min}$ with up to 1.00 °C increases. The results are largely statistically significant. This paper suggests more focus on regional- and local-scale studies is needed to better understand impacts of land use changes on climate change and variability.

## Introduction

Over the last several hundred years, rapid changes in land-use in many parts of the world have played an important role in modifying near surface climate and hydrology (Breyer, Chang, & Parandvash, 2012; Fox et al., 2012; Gao & Liu, 2011, 2012; Klein, Ursula Gessner, & Kuenzer, 2012; Sullivan, Ternan, & Williams, 2004). Marland et al. (2003) noted that these changes would affect regional and global climate by altering surface Albedo and energy budgets. Pielke et al. (2002) suggested that energy partitioning directly influences near surface temperature and should be counted as a climate forcing. As a result, the National Research Council recommended that we include land-use change and impacts within climate change assessments (NRC, 2005). Recently, Mahmood et al. (2010) and Pielke et al. (2011) further highlighted the importance of land-use in the climate system. These assessments also identified the important role of agriculture in land-use change and subsequent impacts on environment including weather and climate.

As expected, the North American continent has experienced significant land-use changes over the last two hundred years. Two key studies by Waisanan & Bliss (2002) and Ramankutty and Foley (1999) inventoried these changes. They have documented rapid transformation of grasslands to agricultural farmlands in the North American Great Plains (GP). The Midwest and the Great Plains experienced 10- and 1-fold changes in land-use between 1850 and 1940 and 1940 and 1997, respectively (Waisanan & Bliss, 2002). Overall they found that the land-use changes represented close to 60% of the total land area. One of the key aspects of land-use change in the Great Plains includes the introduction of irrigation. In some areas (for example, in York County, Nebraska) more than 80% of the land-use has changed from non-irrigated to irrigated agriculture (Mahmood & Hubbard, 2002) and the total calculated change is 23-fold from the 1950s to 1990s (Fig. 1a).

This type of extensive change is quite common in many areas of Nebraska. Parts of western Kansas, Oklahoma, Texas and eastern Wyoming, Colorado, and New Mexico recorded changes where up to 76% of agricultural land-use of a county is under irrigation (National Agricultural Statistics Service). Fig. 1b–f show additional examples of land-use change and irrigation adoption for selected counties that house the USHCN stations used in this study. Fig. 2 shows changes in irrigated land-use in Nebraska. However, these changes and adoption of irrigation varies from one state to another and among counties within these states. Data suggests that in some areas irrigation has been adopted without significantly replacing non-irrigated agriculture (Fig. 1b–f). In some cases irrigated

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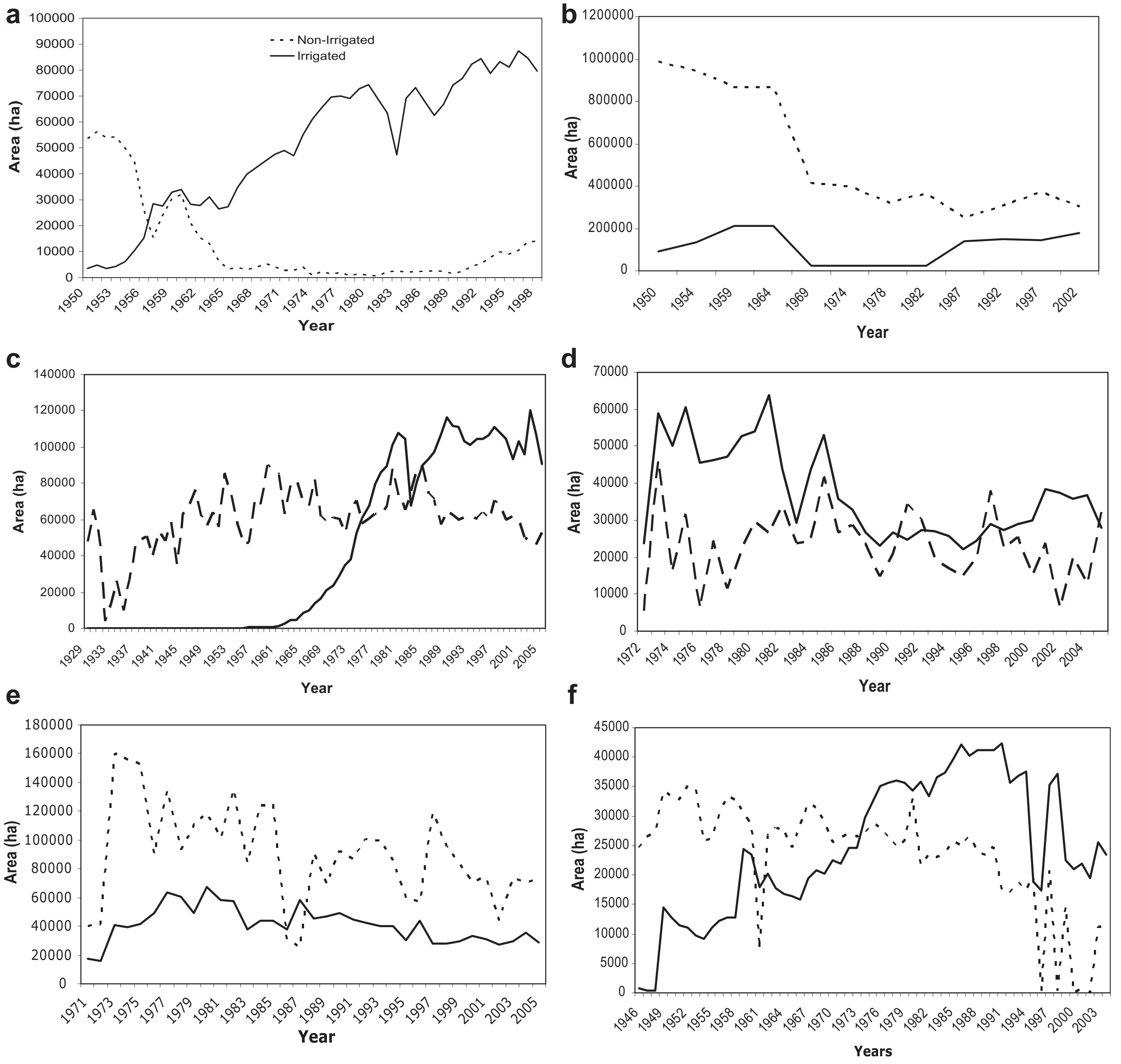

**Fig. 1.** a–f. Land use change in: a) York, Nebraska, b) Eddy, New Mexico, c) Yuma, Colorado, d) Sherman, TX, e) Texas, Oklahoma, and f) Goshen, Wyoming. Broken and unbroken lines represent non-irrigated and irrigated corn land use, respectively.

counties also record substantial presence of non-irrigated agriculture (Fig. 1b–f). Moreover, in many counties and states, total area of land under irrigation went through significant variations over the decades. For example, in Eddy County, New Mexico (home of 'Carlsbad' USHCN station), the land area under irrigation significantly increased through the 1950s and early 1960s and then declined in the 1970s, then started to increase rapidly again through the 1980s and 1990s (Fig. 1b). On the other hand, Texas County, Oklahoma (home of Goodwell and Hooker USHCN sites) shows a gradual decline in irrigated areas in the late 1990s through early 2000s (Fig. 1f).

The High Plains aquifer (HPA) region underlies nearly 20% of all land used for agriculture in the GP and represents 30% of all ground water based irrigation in the United States (The Kerr Center, 2006). The extensive adoption of irrigation in a relatively dry region is expected to partition more net radiation to latent energy and less to sensible energy if incident solar radiation (energy input) remains unchanged. The model applications at climate and meteorological time-scales further verify this expectation (*cf.*, Adegoke, Pielke, Eastman, Mahmood, & Hubbard, 2003; Mahmood & Hubbard, 2002). Fig. 3 shows model estimated annual total evapotranspiration from grass and irrigated corn at McCook, Nebraska. A well-validated energy and water balance model, known as the Robinson–Hubbard (R–H) model (Robinson & Hubbard, 1990), was applied at daily timescales from 1982 through 1999 to derive these estimates. The model requires daily meteorological data including precipitation, humidity, wind speed, temperature, and solar radiation. It also uses data for soil physical properties including bulk density and distribution of clay, silt, and sand and plant phenology information. The results from the R–H model applications suggest that annual total evapotranspiration from the irrigated corn was, on average, 36% greater compared to rain-fed grass at McCook,

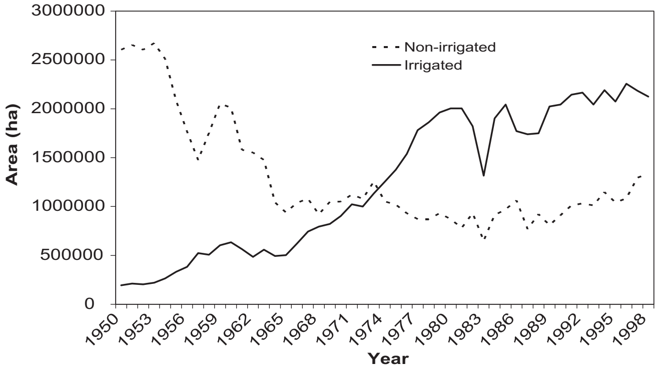

**Fig. 2.** Irrigated and rainfed corn land use in Nebraska (Source: Mahmood & Hubbard, 2002; National Agricultural Statistics Service, 2005).

Nebraska (Fig. 3). Evapotranspiration from irrigated corn was about 34% greater compared to rainfed corn (not shown here). This also suggests that irrigated agriculture could produce much larger impacts on temperature compared to non-irrigated agriculture. This large shift in the magnitude of evapotranspiration taken together with the increasing areal extent of significant evapotranspiration, over a long period of time, is expected to produce trends in the temperature records for stations located in the area. Since irrigation activities commence and end during the growing season (May through September), we expect temperatures to be most affected during this period. In particular, cooling and warming of growing season mean maximum ($GT_{max}$) and minimum temperature ($GT_{min}$) is expected, respectively.

A significant number of model and some observed data-based studies in the past have investigated impacts of land-use change on temperature, large scale atmospheric circulation, and convective activities (e.g., Adegoke, Pielke, & Carleton, 2007; Balling, Klopatek, Hilderbrandt, Moritz, & Watts, 1998; Bounoua et al., 2000, Bounoua, Defries, Collatz, Sellers, & Khan, 2002; Chase, Kittel, Baron, & Stohlgren, 1999; Feddema et al., 2005; Feddema, Oleson, Bonan, Mearns, Washington, et al., 2005; Kanae, Oki, & Katumi, 2001; Lobell, Bala, Duffy 2006; Lobell & Bonfils, 2008; Marshall, Pielke, & Steyaert, 2003, 2004; Pitman, Narisma, Pielke, & Holbrook, 2004; Radaatz, 2003; Raddatz & Cummine, 2003; Roy, Hurtt, Weaver, & Pacala, 2003; Sen, Wang, & Wang, 2004a, b; Twine, 2004; Zhao & Pitman, 2002). However, there is a lack of literature on direct comparison of long-term regional-scale temperature change between irrigated and non-irrigated areas. Therefore, this study investigates the impacts of irrigation on the long-term temperature records of the entire HPA region. This assessment also identifies sub-regional manifestation of impacts of irrigation on both $GT_{max}$ and $GT_{min}$. The additional questions include, do all sub-regions within HPA region show a similar magnitude of cooling of $GT_{max}$ and warming of $GT_{min}$ due to irrigation? Do all sub-regions show continued cooling of $GT_{max}$ and warming of $GT_{min}$ during the 2nd half of the 20th century? Answering these questions will provide us with a better understanding of impacts of irrigation. The analysis presented in this paper is particularly important since impacts of large-scale land-use changes on US temperature due to the introduction of agriculture are far greater than urban impacts (Cai, Li, & Kalnay, 2004).

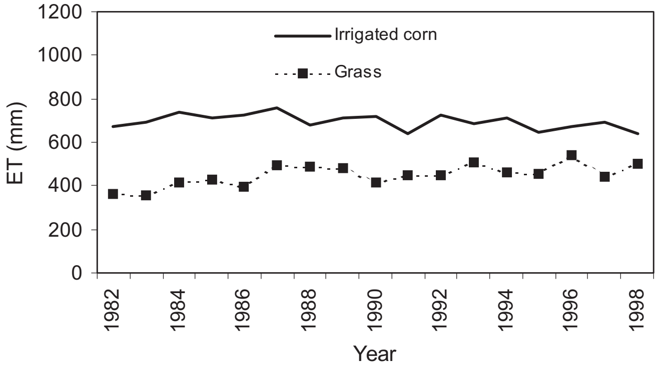

**Fig. 3.** Annual evapotranspiration from irrigated corn and grassland uses at McCook, Nebraska. (Source: modified from Mahmood & Hubbard, 2002).

Mahmood and Hubbard (2002) and Mahmood, Hubbard, and Carlson (2002, 2004) and Mahmood et al., (2006), investigated the impacts of irrigation on soil moisture, evapotranspiration, and long-term temperature records of the Nebraska portion of the HPA region and found land-use transformation to irrigated agriculture has affected long-term temperature records. The results also made it imperative that we investigate the impacts of irrigation over the entire HPA region. This study provides an assessment of the impacts of adoption of irrigation over a large part of the Great Plains (30–43 °N latitude and 94–110 °W longitude) using in-situ observations and thus the potential regional variation of the magnitude of these impacts.

The current study particularly expands on Mahmood et al. (2006). The present assessment intends to determine whether the irrigation forced cooling of $GT_{max}$ in Nebraska is also present in other areas of the HPA region. In Nebraska, the signal for warming of night time temperature ($GT_{min}$) was not very clear. Hence, this study also investigated $GT_{min}$ to determine whether the signal is as complex in other parts of the HPA region. For completeness of this assessment on the entire HPA region, we have also included selected results from Nebraska.

To fulfill the overarching goal of this study, temperature changes in irrigated areas compared to non-irrigated were calculated for the 20th century. It needs to be noted that the length of time series used in this study is longer than for previous studies. In addition, most of the past studies relied heavily on modeling approaches with a clear absence of detailed assessment of temperature observations. The present assessment complements model based research and will fill some of the voids in the literature.

## Data and methodology

The current study uses data from the US Historical Climate Network (USHCN). Data from 50 stations were used to analyze long-term growing season monthly mean maximum ($GT_{max}$) and minimum ($GT_{min}$) temperatures (Fig. 4 and Table 1). Monthly data were used because this study focuses on seasonal time-scale (growing season temperatures, in this case). Of these 50 stations, 24 are located within areas where irrigated agriculture is a significant part of the land-use. The remaining stations (26) represent non-irrigated land-use. These stations have been selected because of their representation of irrigated or non-irrigated land-use, length of the time series, completeness of record, and relative stability of station location. Note, 6 of these 50 stations were used in the Mahmood et al. (2006) study.

It is well-known that USHCN original station data contain bias related to instrument exposure, instrument change, and station move (Hubbard & Lin, 2006; Mahmood et al., 2006; Pielke, Davey, et al., 2007; Pielke, Nielsen, et al., 2007). This study uses the adjusted USHCN monthly data (Easterling, Karl, Mason, Hughes, & Bowman, 1996, pp. 262) which has been modified, based on nearby reference stations, for any change points noted in the station metadata (e.g., station moves). The uncertainties of this adjustment are quantified in Pielke, Nielsen, et al., (2007), however,

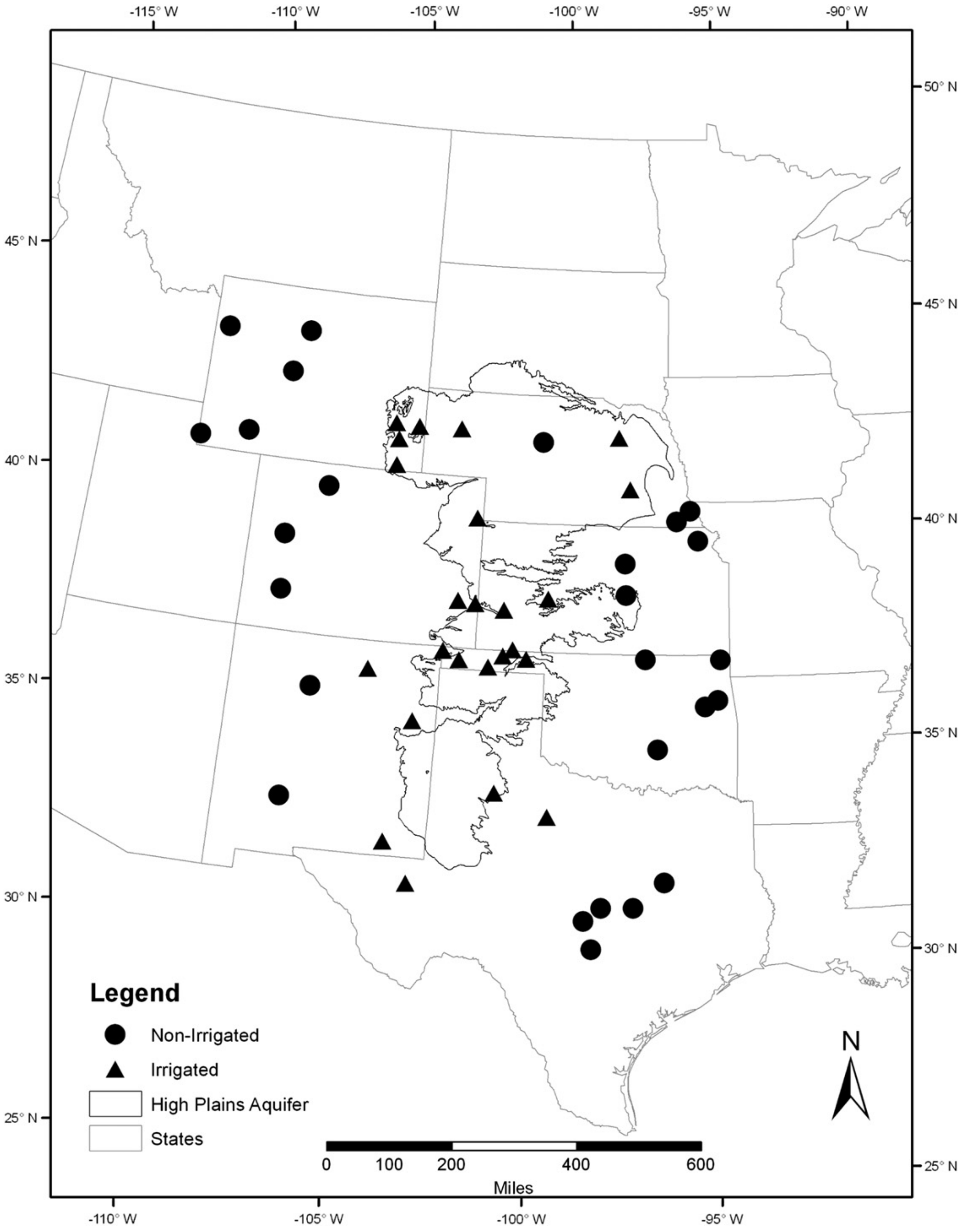

Fig. 4. Meteorological stations and their locations.

in this case the individual areas within the region are selected for their homogeneity so that effects on regional trends are expected to be minor.

The stations are located within the states of Nebraska, Wyoming, Kansas, Colorado, New Mexico, Oklahoma, and Texas. All of the irrigated sites are located within the HPA region. The study has taken several steps to discriminate between irrigated and non-irrigate sites. These include the following:

1) The Census of Agriculture from the National Agricultural Statistics Survey was utilized (http://www.nass.usda.gov/census/). The data is available at the county level.
2) After the data was collected the percent of farmland irrigated for each county was calculated. Stations representing the highly irrigated areas were then chosen from the counties with the highest percent of irrigation. For Nebraska we have also utilized a map of a center pivot irrigation developed for the state by the University of Nebraska-Lincoln (UNL, 2000).
3) Stations representing non-irrigated land-use were selected from counties with no-irrigation or a low percent of irrigation.
4) In addition, Qi, Konduris, Litke, and Dupree (2002; p. 35 p Fig. 15) was used to further verify stations representing irrigated areas and found that these stations were indeed located in these areas.

**Table 1**
List of HCN stations and associated land uses for pairwise comparison.

| Stations | State | Status | Length of timeseries |
|---|---|---|---|
| York | NE | Irrigated | 1906–1999 |
| Oakdale | NE | Irrigated | 1906–1999 |
| Alliance | NE | Irrigated | 1906–1999 |
| Halsey | NE | Non-irr. | 1906–1999 |
| Auburn | NE | Non-irr. | 1906–1999 |
| Pawnee City | NE | Non-irr. | 1906–1999 |
| Holly | CO | Irrigated | 1899–1994 |
| Wray | CO | Irrigated | 1893–1994 |
| Lamar | CO | Irrigated | 1893–1994 |
| Steamboat Springs | CO | Non-irr. | 1894–1994 |
| Collbran | CO | Non-irr. | 1900–1994 |
| Telluride | CO | Non-irr. | 1900–1994 |
| Torrington Exp Farm | WY | Irrigated | 1922–1994 |
| Chugwater | WY | Irrigated | 1900–1994 |
| Wheatland 4 N | WY | Irrigated | 1906–1994 |
| Cheyenne WSFO | WY | Irrigated | 1885–1994 |
| Riverton | WY | Non-irr. | 1907–1994 |
| Evanston 1 E | WY | Non-irr. | 1899–1994 |
| Green River | WY | Non-irr. | 1910–1994 |
| Worland | WY | Non-irr. | 1907–1994 |
| Moron 5 WNW | WY | Non-irr | 1911–1994 |
| Tucumcari 4 NE | NM | Irrigated | 1905–1994 |
| Carlsbad | NM | Irrigated | 1900–1994 |
| Elephant Butte Dam | NM | Non-irr. | 1908–1994 |
| Jemez Springs | NM | Non-irr. | 1910–1994 |
| Boise City 2 E | OK | Irrigated | 1908–1994 |
| Kenton | OK | Irrigated | 1900–1994 |
| Goodwell Research St. | OK | Irrigated | 1910–1994 |
| Hooker | OK | Irrigated | 1906–1994 |
| Beaver | OK | Irrigated | 1906–1994 |
| Tahlequah | OK | Non-irr. | 1894–1994 |
| Muskogee | OK | Non-irr. | 1899–1994 |
| Newkrik | OK | Non-irr. | 1897–1994 |
| Ada | OK | Non-irr. | 1907–1994 |
| Miami | OK | Non-irr. | 1917–1994 |
| Crosbyton | TX | Irrigated | 1897–1994 |
| Stratford | TX | Irrigated | 1915–1994 |
| Haskell | TX | Irrigated | 1897–1994 |
| Pecos | TX | Irrigated | 1913–1994 |
| Mexia | TX | Non-irr. | 1904–1994 |
| Llano | TX | Non-irr. | 1902–1994 |
| Temple | TX | Non-irr. | 1893–1994 |
| Blanco | TX | Non-irr. | 1896–1994 |
| Lampasas | TX | Non-irr. | 1896–1994 |
| Jetmore 12 NNW | KS | Irrigated | 1904–1994 |
| Lakin | KS | Irrigated | 1893–1994 |
| Liberal | KS | Irrigated | 1893–1994 |
| Horton | KS | Non-irr. | 1893–1994 |
| Mcpherson | KS | Non-irr. | 1893–1994 |
| Minneapolis | KS | Non-irr. | 1892–1994 |

All of the USHCN stations used in this study are not representing areas with equally extensive irrigated agriculture because all of the counties (where the USHCN stations are located) did not adopt irrigation in the same manner. As a result, we do not expect that all USHCN stations will show similar magnitude of impacts of irrigation on temperatures.

Since impacts of multiple forcings can cancel each other, pairwise comparisons help to identify impacts on temperature records taken over dissimilar land surfaces. Frequently, prevailing large-scale synoptic pattern affects temperature of a region during a particular season [in this case, growing season (May through September)] and it is expected that impacts would be felt at both irrigated and non-irrigated sites. Pairwise comparison of temperature would otherwise cancel the similar affects. However, sites representing pre-dominantly irrigated land will reflect the smaller amount of energy partitioned into sensible heat while sites dominated by non-irrigated land-use would reflect the larger amount of sensible heat. Thus, to accomplish the objective of the study pairwise comparisons of $GT_{max}$ and $GT_{min}$ for non-irrigated and irrigated locations were completed.

From the 1940s through the 1950s the Great Plains experienced significant change from non-irrigated to irrigated agriculture. As a result, in the past (Mahmood et al., 2006) and for this study, we have divided and analyzed the entire time series for each locations into pre- and post-1945, pre- and post-1950, and pre and post-1955 to best capture irrigation adoption in the HPA region and subsequent impacts on temperature. These three sets of analysis for the entire data set also served as a sensitivity test (first) for selection of a dividing year. It is found that when these time series were divided between pre- and post-1945, they reflected the irrigation impacts most satisfactorily (Mahmood et al., 2006). Hence, authors of this study presented results only from pre- and post-1945.

Moreover, it is well known that northerly located stations are going to be generally cooler compared to southerly sites due to latitudinal distribution of solar irradiance. To eliminate or reduce this effect, station selection for pairwise comparison was limited to stations within the same state. In other words, temperatures from Nebraska's irrigated sites were compared to non-irrigated locations in Nebraska only. It allowed all irrigated and non-irrigated site comparisons within Nebraska, Wyoming, Colorado, Kansas, and Oklahoma to be located latitudinally within 2° of each other. There is one station in New Mexico within 3° of others and the three stations in Texas are outside of this 2° range (two within 3° and one within 4°). Thus, range of latitudinal distribution is only about 2° for most of the stations (46 total) and analyses are completed for warm months only, when impact of this latitudinal distribution on temperature is almost non-existent (*cf.*, Balling, 1988). Over the HPA region longitudinal variations of temperature during warm months is nearly non-existent and thus is not a significant source of bias in this study [Southern Regional Climate Center, 2012, (http://www.srcc.lsu.edu/climate_normals.html)].

In addition, potential of bias in the outcome is removed when temperature time series were divided between pre- and post-1945 and subsequent calculation of magnitude of cooling for each segment and for each pair. Suppose, a northerly located irrigated location is 1 °C cooler compared to a southerly located non-irrigated site during the first half of the 20th century. Furthermore, during the second-half of the 20th century it is, say, 2 °C cooler. Now, it is possible to conclude that there is a 1 °C cooling and the impact of latitude has been removed in the calculation.

In this paper, 'cooling' refers to a condition when irrigated locations were cooler compared to non-irrigated locations during pre-1945 and further cooling occurred during post-1945. For example, an irrigated location could be −2.00 °C cooler compared to a non-irrigated location during pre-1945 period. If this irrigated site is −2.20 °C cooler compared to the same non-irrigated site during post-1945 then there was an additional −0.20 °C cooling during the post-1945 period. This is 'cooling' in this manuscript. On the other hand, irrigated locations could be 'cooler' compared to non-irrigated locations for both pre- and post-1945 period. However, it is possible that irrigated locations are less cool compared to non-irrigated locations during post-1945. For example, an irrigated site could be −2.00 °C cooler compared to a non-irrigated site during pre-1945 period. However, if irrigated site is −1.80 °C cooler compared to the same non-irrigated site then warming has occurred (+0.20 °C). Overall, the irrigated site is cooler during both pre- and post-1945, although there was a net warming. In this case, we have used 'lower $GT_{max}$' instead of cooling. We have also used 'lower $GT_{max}$' when 'cooling' was not clear-cut.

In addition to the above mentioned uncertainties associated with the temperature data set and history of irrigated land-use change (i.e., scale and rate of change over time) and despite the advantages of pairwaise comparison, we suspect that the impacts of regional topography (e. g., channeling of air flow from mountains to valleys – particularly in western Wyoming and western Colorado), scale of irrigation (small vs. large), interactions of micro- vs. regional-scale influences (particularly opposite ones – associated with instrument exposure), background dryness or wetness due to irrigation, are unknown in this study.

To verify the outcome, statistical significance tests (confidence level 95%) were completed for all pairwise comparisons. For additional verification, the bootstrapping method (*cf.*, Mooney & Duval, 1993) is applied. Bootstrapping permitted re-sampling of the data from each location for $GT_{max}$ and $GT_{min}$. For each of the parameters at each location 1000 data sets were created through re-sampling. To eliminate the affects of extreme values, this study adopted Yuen-Welch's trimmed mean approach (Wilcox, 1997). We decided to exclude 20% of the extreme values from each tail of the re-sampled temperature data (20%-trimmed mean approach). Subsequently, comparisons of results (significant at 95%) were made between the original distribution and the trimmed re-sampled distribution. Similarity of results from these trimmed re-sampled data sets and the original data sets provided additional assurance on the reliability of the outcome. Furthermore, these analyses (comparison between original and trimmed data sets) also served as a second sensitivity test for our results.

Note, as an estimate of the location of the center of a population distribution, the sample mean can be interpreted as a value that is representative, or typical, of the values in a symmetric, uni-modal distribution. If the sample distribution is well behaved, lacking long tails with outliers, then the sample mean is a desirable measure. Otherwise the undue influence of extreme values may call for the use of a more robust measure of central tendency. A trimmed mean makes sense, because it uses only the more typical portions of the distribution to produce a measure of its center. Recognizing the complex factors that may be implicated in the recorded temperature data at various observing sites, we chose to supplement the use of a traditional statistical test with the use of a robust test in an effort to increase confidence in the results we obtained.

We have also completed analysis for COOP data from the same locations and compared with findings from HCN data. Detailed results from COOP data sets were not reported in this paper. Please note that HCN data set used here is derived from COOP data after bias correction. As a result, the COOP data set could be viewed as ‘raw’. We were curious to see how different the results were between ‘raw’ (COOP) and bias corrected (HCN) data. Since COOP data goes through some basic screening, qualitatively speaking, it was expected that the results should not be significantly different. It was found that the results were generally similar. This assessment has served as the third sensitivity test.

## Results

### *Growing season mean maximum temperature ($GT_{max}$)*

Overall, during the 2nd half of the 20th century, the majority of irrigated locations recorded cooler (56 of 96 pairwise comparisons; 58%) $GT_{max}$ compared to their non-irrigated counterparts (Table 2). Slightly more pronounced impacts can be found in the case of more arid states (Colorado, Kansas, Nebraska, and New Mexico) where 19 of 31 pairwise comparisons (61%) suggests cooler $GT_{max}$ at irrigated locations during the 2nd half of the 20th century (Table 2).

Nebraska shows continuation of cooling during the 2nd half of the 20th century. Nebraska exhibited the largest cooling at irrigated locations where $GT_{max}$ at irrigated sites are up to 2.97 °C cooler compared to non-irrigated sites during post-1945 years (Table 2).

**Table 2**

Differences in growing season mean maximum temperatures ($GT_{max}$) of irrigated and non-irrigated during pre- and post-1945 period. ‘*’ indicates results from observed data are significant at 95% level. ‡ indicates results significant at 95% after bootstrap re-sampling and 20% trimming (robust statistics). † indicates results from observed and re-sampled data agree, however, they are not statistically significant. Negative sign suggests overall cooler temperatures.

| Irrigated – non-irrigated $GT_{max}$ (°C) | Irrigated – non-irrigated pre-1945 $GT_{max}$ (°C) | Irrigated – non-irrigated post-1945 $GT_{max}$ (°C) | Difference $GT_{max}$ (°C) |
|---|---|---|---|
| *Nebraska* | | | |
| Alliance–Auburn | −2.41 | −2.22 | 0.19† |
| Alliance – Halsey | −0.64 | −1.65 | −1.01*‡ |
| Alliance – Pawnee | −2.32 | −2.97 | −0.65*‡ |
| Oakdale–Auburn | −2.32 | −1.86 | 0.46*‡ |
| Oakdale–Halsey | −0.62 | −1.25 | −0.63* |
| Oakdale–Pawnee | −2.18 | −2.64 | −0.46*‡ |
| York–Auburn | −0.05 | −0.49 | −0.44*‡ |
| York–Halsey | 1.59 | 0.18 | −1.41*‡ |
| York–Pawnee | 0.03 | −1.23 | −1.26*‡ |
| *Kansas* | | | |
| Jetmore – Horton | 1.92 | 1.60 | −0.32† |
| Jetmore – McPherson | 0.21 | 0.36 | 0.15† |
| Jetmore – Minneapolis | 0.29 | 0.00 | −0.29† |
| Lakin – Horton | 2.26 | 1.72 | −0.54* |
| Lakin – McPherson | 0.55 | 0.48 | −0.07† |
| Lakin – Minneapolis | 0.63 | 0.12 | −0.51* |
| Liberal – Horton | 2.07 | 2.61 | 0.54*‡ |
| Liberal – McPhersson | 0.36 | 1.37 | 1.01*‡ |
| Liberal – Minneapolis | 0.44 | 1.01 | 0.57*‡ |
| *New Mexico* | | | |
| Carlsbad – Elephant | 1.91 | 1.65 | −0.26† |
| Carlsbad – Jemez Spring | 4.74 | 5.11 | 0.37* |
| Tucamcari – Elephant | 0.35 | −0.63 | −0.98*‡ |
| Tucamcari – Jemez Spr. | 3.18 | 2.83 | −0.35* |
| *Wyoming* | | | |
| Cheyenne–Evanston | 0.58 | 0.66 | 0.08† |
| Cheyenne–Green River | −2.02 | −1.50 | 0.52*‡ |
| Cheyenne–Moran | 2.91 | 3.70 | 0.79*‡ |
| Cheyenne–Riverton | −3.51 | −3.04 | 0.47*‡ |
| Cheyenne–Worland | −4.53 | −3.67 | 0.86*‡ |
| Chugwater–Evanston | 2.32 | 2.46 | 0.14† |
| Chugwater–Green River | −0.28 | 0.30 | 0.58*‡ |
| Chugwater–Moran | 4.65 | 5.50 | 0.85*‡ |
| Chugwater–Riverton | −1.77 | −1.24 | 0.53*‡ |
| Chugwater–Worland | −2.79 | −1.87 | 0.92*‡ |
| Torrington–Evanston | 3.06 | 3.67 | 0.61* |
| Torrington–Green River | −0.46 | 1.51 | 1.05*‡ |
| Torrington–Moran | 5.39 | 6.71 | 1.32*‡ |
| Torrington–Riverton | −1.03 | −0.03 | 1.00*‡ |
| Torrington–Worland | −2.05 | −0.66 | 1.39*‡ |
| Wheatland–Evanston | −6.23 | −6.21 | 0.02‡ |
| Wheatland–Green River | −8.83 | −8.37 | 0.46† |
| Wheatland–Moran | −3.90 | −3.17 | 0.73* |
| Wheatland–Riverton | −10.32 | −9.91 | 0.41‡ |
| Wheatland–Worland | −11.34 | −10.54 | 0.80* |
| *Colorado* | | | |
| Holly–Collbran | 3.11 | 3.95 | 0.84*‡ |
| Lamar–Steamboat Spr. | 5.64 | 6.34 | 0.70*‡ |
| Ray–Telluride | 8.71 | 8.42 | −0.29† |
| Holly–Collbran | 4.67 | 4.89 | 0.22† |
| Lamar–Steamboat Spr. | 7.20 | 7.28 | 0.08† |
| Ray–Telluride | 10.27 | 9.36 | −0.91*‡ |
| Holly–Collbran | 0.94 | 1.54 | 0.60*‡ |
| Lamar–Steamboat Spr. | 3.47 | 3.93 | 0.46* |
| Ray–Telluride | 6.54 | 6.01 | −0.53*‡ |
| *Oklahoma* | | | |
| Beaver–Ada | −0.33 | 0.24 | 0.57*‡ |
| Beaver–Miami | 0.22 | 0.70 | 0.48* |
| Beaver–Muskogee | −0.30 | −0.12 | 0.18† |
| Beaver–Newkirk | −0.73 | 0.26 | 0.99*‡ |
| Beaver–Tahlequah | −0.42 | 0.74 | 1.16*‡ |
| Boise–Ada | −1.24 | −0.96 | 0.28† |
| Boise–Miami | −0.69 | −0.50 | 0.19† |
| Boise–Muskogee | −1.21 | −1.32 | −0.11† |
| Boise–Newkirk | −1.64 | −0.94 | 0.70*‡ |
| Boise–Tahlequah | −1.33 | −0.46 | 0.87*‡ |

**Table 2** (*continued*)

| Irrigated − non-irrigated GT$_{\max}$ (°C) | Irrigated − non-irrigated pre-1945 GT$_{\max}$ (°C) | Irrigated − non-irrigated post-1945 GT$_{\max}$ (°C) | Difference GT$_{\max}$ (°C) |
|---|---|---|---|
| Goodwell–Ada | −0.77 | −0.41 | 0.36‡ |
| Goodwell–Miami | −0.22 | 0.05 | 0.27† |
| Goodwell–Muskogee | −0.74 | −0.77 | −0.03† |
| Goodwell–Newkirk | −1.17 | −0.39 | 0.78*‡ |
| Goodwell–Tahlequah | −0.86 | 0.09 | 0.95*‡ |
| Hooker–Ada | −0.37 | 0.16 | 0.53*‡ |
| Hooker–Miami | 0.18 | 0.62 | 0.44† |
| Hooker–Muskogee | −0.34 | −0.20 | 0.14† |
| Hooker–Newkirk | −0.77 | 0.18 | 0.95*‡ |
| Hooker–Tahlequah | −0.46 | 0.66 | 1.12*‡ |
| Kenton–Ada | −1.50 | −0.79 | 0.71*‡ |
| Kenton–Miami | −0.95 | −0.33 | 0.62* |
| Kenton–Muskogee | −1.47 | −1.15 | 0.32† |
| Kenton–Newkirk | −1.90 | −0.77 | 1.13*‡ |
| Kenton–Tahlequah | −1.45 | −0.29 | 1.30*‡ |
| *Texas* | | | |
| Crosbyton–Blanco | −1.55 | −1.02 | 0.53* |
| Crosbyton–Lampasas | −1.51 | −1.25 | 0.26† |
| Crosbyton–Llano | −2.93 | −2.30 | 0.63*‡ |
| Crosbyton–Mexia | −2.13 | −2.13 | 0.00† |
| Crosbyton–Temple | −1.62 | −1.59 | 0.03† |
| Haskell–Blanco | −0.31 | 0.70 | 1.01*‡ |
| Haskell–Lampasas | −0.27 | 0.47 | 0.74*‡ |
| Haskell–Llano | −1.69 | −0.58 | 1.11*‡ |
| Haskell–Mexia | −0.89 | −0.41 | 0.48* |
| Haskell–Temple | −0.38 | 0.13 | 0.51* |
| Pecos–Blanco | 0.43 | 3.01 | 2.58*‡ |
| Pecos–Lampasas | 0.47 | 2.78 | 2.31*‡ |
| Pecos–Llano | −0.95 | 1.73 | 2.68*‡ |
| Pecos–Mexia | −0.15 | 1.90 | 2.05*‡ |
| Pecos–Temple | 0.36 | 2.44 | 2.08*‡ |
| Stratford–Blanco | −3.26 | −3.10 | 0.16† |
| Stratford–Lampasas | −3.22 | −3.33 | −0.11† |
| Stratford–Llano | −4.64 | −4.38 | 0.26† |
| Stratford–Mexia | −3.84 | −4.21 | 0.37† |
| Stratford–Temple | −3.33 | −3.67 | 0.34† |

It is found that during pre-and post-1945, GT$_{\max}$ at irrigated Alliance was 0.64 °C and 1.65 °C cooler compared to non-irrigated Halsey, respectively. Hence, 1.01 °C (level of significance 95%) cooling of GT$_{\max}$ has occurred during post-1945 years (Fig. 5). A composite analysis of data also shows greater cooling during post-1945, and on the average, irrigated locations cooled down 0.58 °C (Table 3).

New Mexico shows that there has been a lowering of GT$_{\max}$ of up to 0.98 °C (level of significance 95%) over irrigated locations during the second half of 20th century (Fig. 6). Composite analysis also suggests 0.31 °C cooling (Table 3). Data from Kansas also indicates lowering of GT$_{\max}$ up to 0.54 °C (level of significance 95%) at irrigated locations during post-1945 period (Fig. 7). Hence, over all, the magnitude of cooling is more prominent in Nebraska (Table 3).

Composite analysis for Wyoming shows, compared to non-irrigated sites, GT$_{\max}$ was 1.28 °C lower over irrigated locations during the second half 20th century (Fig. 8). GT$_{\max}$ analyses for Oklahoma also show that irrigated locations were lower compared to non-irrigated. Pairwise comparisons of GT$_{\max}$ from irrigated and non-irrigated sites in Texas show results that are somewhat similar to the findings from Oklahoma. It is found that 12 of 20, 15 of 25, and 12 of 20 pairwise comparisons for Wyoming, Oklahoma, and Texas suggest lower GT$_{\max}$ in irrigated locations. Thus, the majority of irrigated locations show cooler GT$_{\max}$. In Oklahoma and Texas, the difference between pre and post-1945 indicated a warming at the majority of sites (Table 2).

Despite lower GT$_{\max}$ temperatures at the large majority of irrigated locations, lowering did not continue in many of these locations during the 2nd half of the 20th century. It is evident in the fact that, overall, irrigated locations in Texas were 1.57 and 0.74 °C cooler during pre-1945 period and post-1945 period, respectively (Table 3). Hence, 0.83 °C warming has occurred. Only 21 pairwise comparisons (of total 96) show continuation of lowering of GT$_{\max}$ during 2nd half of the 20th century. Instead of a sweeping continuation of lowering of GT$_{\max}$ or cooling over entire HP region, this study finds regional manifestation, i.e, cooling continued in some irrigated areas (e. g., Nebraska) while GT$_{\max}$ remained lower but did not continue the cooling trend (e. g., Texas). Further explanation is provided in section 4.

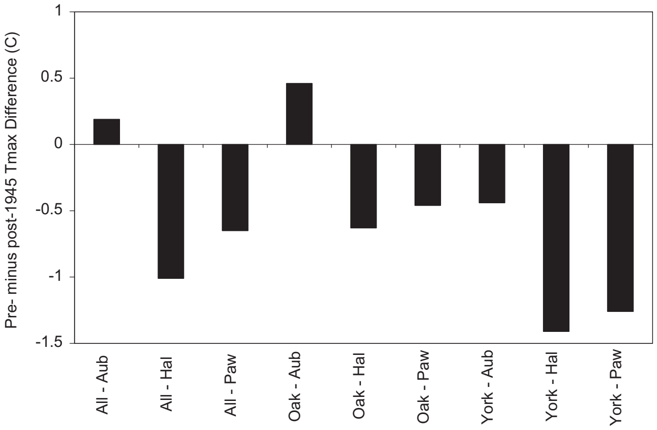

**Fig. 5.** Difference between growing season mean maximum temperatures at irrigated (Alliance, Oakland, and York) and non-irrigated locations for pre-1945 minus difference between growing season mean maximum temperatures at irrigated and non-irrigated locations for post-1945 years in Nebraska. All results are significant at 95% level except for 'All–Aub' (Alliance–Auburn). (Source: Mahmood et al., 2006).

Bootstrap re-sampling and 20% trimmed mean based further assessment of statistical significance of results largely agreed with similar tests based on observed data. It is found that 79 of 96 observed data-based pairwise comparison results for GT$_{\max}$ agree with re-sampled data-based statistical significance tests (including statistically significant and not significant) (Table 2).

### *Growing season mean minimum temperature (GT$_{\min}$)*

Nebraska, Kansas, and New Mexico have experienced more cooling (8 of the 11 significant differences) of the minimum temperature in post-1945 compared to pre-1945 (Table 4). On the other hand, analysis of data from Texas finds that 18 of 20 pairs experienced warming up to 1.00 °C (level of significance 95%) during post-1945 period (Fig. 9). Composite analysis of GT$_{\min}$ data indicates that irrigated sites have become 0.51 °C warmer in Texas during post-1945 period (Table 5).

Pairwise analyses of GT$_{\min}$ for Nebraska indicates that in seven out of nine cases irrigated land-use was up to 5.03 °C cooler than

**Table 3**
Composite differences in growing season mean maximum temperatures (GT$_{\max}$) of irrigated and non-irrigated during pre- and post-1945 period. Negative sign indicates overall cooling.

| State | Irrigated − non-irrigated pre-1945 GT$_{\max}$ (°C) | Irrigated − non-irrigated post-1945 GT$_{\max}$(°C) | Difference |
|---|---|---|---|
| Nebraska | −0.99 | −1.57 | −0.58 |
| Wyoming | −1.96 | −1.28 | 0.68 |
| Kansas | 0.97 | 1.03 | 0.06 |
| Colorado | 5.62 | 5.75 | 0.13 |
| New Mexico | 2.55 | 2.24 | −0.31 |
| Oklahoma | −0.82 | −0.23 | 0.59 |
| Texas | −1.57 | −0.74 | 0.83 |

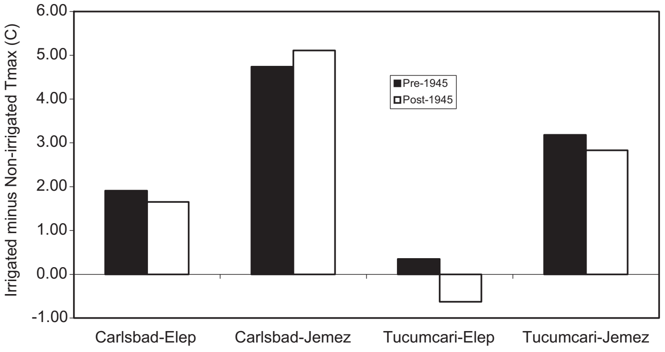

**Fig. 6.** Irrigated (Carlsbad and Tucumcari) minus non-irrigated location growing season mean maximum temperatures for pre- and post-1945 years in New Mexico.

non-irrigated sites during pre-1945 (Table 4). For post-1945 years five pairwise comparisons suggest warming while composite analysis found, on the average, nearly no warming over irrigated areas (Table 5). During the post-1945 period $GT_{min}$ remains higher in most irrigated sites in Wyoming (Table 4) compared to non-irrigated locations, however, a very mild overall cooling (0.01 °C) also appeared during post-1945 (Table 5). It is found that 12 of 20 pairs for Wyoming experienced warming up to 1.00 °C (level of significance 95%) in $GT_{min}$ for the post-1945 period (Fig. 10). In other words, irrigated sites in Wyoming have generally become warmer than non-irrigated sites during post-1945 years. In addition, irrigated sites of New Mexico experience 0.30 °C warming of $GT_{min}$ during the second half of 20th century (Table 5). Thus, based on composite analysis, Texas shows more warming than other regions (Table 5). As opposed to Texas, Nebraska, and Wyoming, most of irrigated locations in Oklahoma suggest a cooling of $GT_{min}$ during second-half of the 20th century.

Of 96 pairwise comparisons, 49 show continuation of warming of $GT_{min}$ during post-1945 and thus provide evidence of irrigation forcing. Physically, it is consistent with our understanding regarding the role of soil moisture and the associated changes in heat capacity as well as the role of potentially higher dew points over irrigated areas. In addition, like $GT_{max}$, bootstrap re-sampling and 20% trimmed mean-based further assessment of statistical significance of results largely agreed with similar tests based on observed data. It is found that 87 of 96 observed data-based pairwise comparison results for $GT_{min}$ agree with re-sampled data-based statistical significance tests (including statistically significant and not significant) (Table 4).

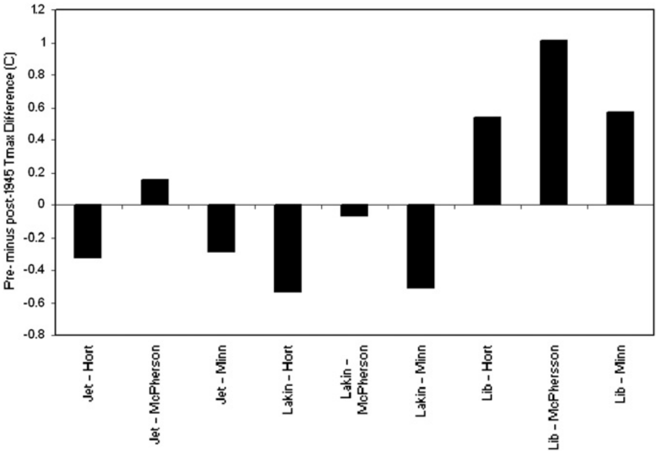

**Fig. 7.** Difference between growing season mean maximum temperatures at irrigated (Jetmore, Lakin, and Liberal) and non-irrigated locations for pre-1945 minus difference between $GT_{max}$ irrigated and non-irrigated locations for post-1945 years in Kansas.

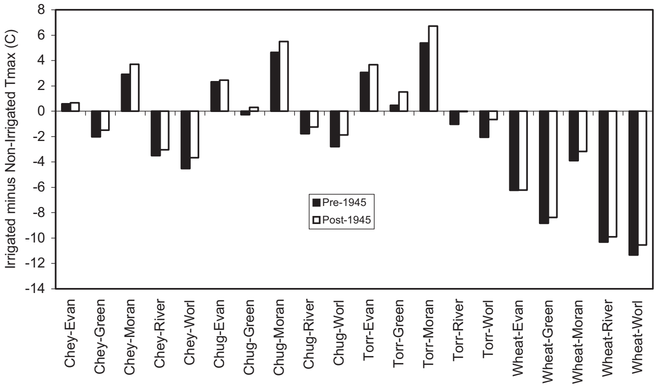

**Fig. 8.** Irrigated (Cheyenne, Chugwater, Torrington, and Wheatland) minus non-irrigated location growing season mean maximum temperatures for pre- and post-1945 years in Wyoming.

## Discussion and final remarks

This study provides a unique opportunity to assess potential changes in temperatures due to introduction of irrigation in the HPA region. Pairwise comparisons of data from the High Plains aquifer region suggest regional variations of irrigation influence on $GT_{max}$ during 2nd half of 20th century. For example, in Nebraska cooling of $GT_{max}$ at irrigated locations was greater during the 2nd half of 20th century (Table 2). On other hand, in some locations there was lowering of $GT_{max}$. Moreover, magnitude of cooling is twice as much greater in Nebraska compared to some of the other regions. Based on analysis, the $GT_{max}$ remained lower for majority of pairs in Wyoming (12 of 20), Texas (12 of 20) and Oklahoma (15 of 25) during the 2nd half of 20th century. However, the $GT_{max}$ lowering relative to non-irrigated sites did not continue in many of these irrigated locations. Thus, the irrigation forced cooling signal for $GT_{max}$ is not as clear as expected and it is complex and potentially a function of a variety of factors including history of local land-use change. The clear signal of continued cooling of $GT_{max}$ in Nebraska, found by Mahmood et al. (2006) and shown here, is not applicable to entire HP region apparently because other factors superimposed on irrigation forcing partially canceled the irrigation affect (i. e., cooling of $GT_{max}$). In addition, station exposure, instrumentation change, varied history of local land-use change and unintended errors introduced during bias correction—all contributed to the uncertainties in results presented here. In a sense, this paper also highlights the challenges associated with conducting research with historical in-situ observations considered to be of high-quality.

This study found that 49 of 96 pairwise comparisons (Table 4) show continuation of warming of $GT_{min}$ during 2nd half of the 20th century due to irrigation. The majority of pairwise comparisons from Nebraska, Wyoming, and Texas indicate warming at irrigated locations. Hence, after expanding the study to entire HPA region, $GT_{min}$ provides an improved signal of irrigation forced warming compared to Mahmood et al. (2006). Similar to $GT_{max}$, it also shows notable regional variations in magnitude of warming in response to land-use change. For example, warming of $GT_{min}$ in Texas is notably greater than other areas showing warming.

We can speculate that the dew point in Texas and Oklahoma was already high prior to the introduction of irrigation so that less increase in dew point was realized by adding significant irrigated land. This might have led to less cooling of the maximum.

**Table 4**
Differences in growing season mean minimum temperatures ($GT_{min}$) of irrigated and non-irrigated during pre- and post-1945 period. '*' indicates results significant at 95%level. ‡ indicates results significant at 95% after bootstrap re-sampling and 20% trimming (robust statistics). † indicates results from observed and re-sampled agree, however, they are not statistically significant. Negative sign suggests overall cooler temperatures.

| Irrigated − non-Irrigated $GT_{min}$ (°C) | Irrigated − non-irrigated pre-1945 $GT_{min}$ (°C) | Irrigated − non-irrigated post-1945 $GT_{min}$ (°C) | Difference $GT_{min}$ (°C) |
|---|---|---|---|
| *Nebraska* | | | |
| Alliance–Auburn | −4.96 | −4.76 | 0.20† |
| Alliance – Halsey | −1.67 | −1.06 | 0.61*‡ |
| Alliance – Pawnee | −5.03 | −5.25 | −0.22† |
| Oakdale–Auburn | −2.00 | −2.39 | −0.39*‡ |
| Oakdale–Halsey | 1.29 | 1.42 | 0.13† |
| Oakdale–Pawnee | −2.08 | −2.79 | −0.71*‡ |
| York–Auburn | −0.46 | −0.42 | 0.04† |
| York–Halsey | 2.82 | 3.36 | 0.54*‡ |
| York–Pawnee | −0.58 | −0.86 | −0.28* |
| *Kansas* | | | |
| Jetmore – Horton | 0.29 | −0.17 | −0.46* |
| Jetmore – McPherson | −0.82 | −0.87 | −0.05† |
| Jetmore – Minneapolis | −0.91 | −0.85 | 0.06† |
| Lakin – Horton | −0.01 | −0.78 | −0.77*‡ |
| Lakin – McPherson | −1.12 | −1.48 | −0.36*‡ |
| Lakin – Minneapolis | −1.21 | −1.46 | −0.25*‡ |
| Liberal – Horton | 0.63 | 0.25 | −0.38*‡ |
| Liberal – McPhersson | −0.48 | −0.45 | 0.03† |
| Liberal – Minneapolis | −0.57 | −0.43 | −0.14† |
| *New Mexico* | | | |
| Carlsbad – Elephant | −0.87 | 0.02 | 0.89* |
| Carlsbad – Jemez Spring | 6.14 | 7.11 | 0.97* |
| Tucamcari – Elephant | −1.59 | −1.95 | −0.36*‡ |
| Tucamcari – Jemez Spr. | 5.42 | 5.14 | −0.28† |
| *Wyoming* | | | |
| Cheyenne–Evanston | 5.57 | 5.03 | −0.54*‡ |
| Cheyenne–Green River | 3.18 | 3.22 | 0.04† |
| Cheyenne–Moran | 6.05 | 6.16 | 0.11† |
| Cheyenne–Riverton | 1.10 | 1.87 | 0.86*‡ |
| Cheyenne–Worland | −0.82 | −0.24 | 0.58*‡ |
| Chugwater–Evanston | 3.86 | 3.46 | −0.40*‡ |
| Chugwater–Green River | 1.47 | 1.65 | 0.18† |
| Chugwater–Moran | 4.34 | 4.59 | 0.25† |
| Chugwater–Riverton | −0.7 | 0.3 | 1.00*‡ |
| Chugwater–Worland | −2.53 | −1.81 | 0.72*‡ |
| Torrington–Evanston | 6.34 | 5.31 | −1.03*‡ |
| Torrington–Green River | 3.95 | 3.50 | −0.45* |
| Torrington–Moran | 6.82 | 6.44 | −0.38* |
| Torrington–Riverton | 1.78 | 2.15 | 0.37*‡ |
| Torrington–Worland | −0.05 | 0.04 | 0.09† |
| Wheatland–Evanston | 6.14 | 5.06 | −1.08*‡ |
| Wheatland–Green River | 3.75 | 3.25 | −0.50*‡ |
| Wheatland–Moran | 6.62 | 6.19 | −0.43* |
| Wheatland–Riverton | 1.58 | 1.9 | 0.32† |
| Wheatland–Worland | −0.25 | −0.21 | 0.04† |
| *Colorado* | | | |
| Holly–Collbran | 6.47 | 5.81 | −0.66*‡ |
| Lamar–Steamboat Spr. | 13.66 | 11.73 | −1.93*‡ |
| Ray–Telluride | 13.12 | 11.05 | −2.07*‡ |
| Holly–Collbran | 3.12 | 4.30 | 1.18*‡ |
| Lamar–Steamboat Spr. | 10.31 | 10.22 | −0.09† |
| Ray–Telluride | 9.77 | 9.54 | −0.23† |
| Holly–Collbran | 3.39 | 4.56 | 1.17*‡ |
| Lamar–Steamboat Spr. | 10.58 | 10.48 | −0.10† |
| Ray–Telluride | 10.04 | 9.80 | −0.24† |
| *Oklahoma* | | | |
| Beaver–Ada | −3.07 | −2.41 | 0.66*‡ |
| Beaver–Miami | −0.71 | −0.62 | 0.09† |
| Beaver–Muskogee | −1.37 | −1.83 | −0.46† |
| Beaver–Newkirk | −1.81 | −2.12 | −0.31† |
| Beaver–Tahlequah | −0.82 | −1.26 | −0.44† |
| Boise–Ada | −5.45 | −5.07 | 0.38*‡ |
| Boise–Miami | −3.09 | −3.28 | −0.19† |
| Boise–Muskogee | −3.75 | −4.49 | −0.74† |
| Boise–Newkirk | −4.19 | −4.78 | −0.59† |
| Boise–Tahlequah | −3.20 | −3.92 | −0.72† |
| Goodwell–Ada | −4.48 | −3.85 | 0.63*‡ |
| Goodwell–Miami | −2.12 | −2.06 | 0.06† |
| Goodwell–Muskogee | −2.78 | −3.27 | −0.49† |
| Goodwell–Newkirk | −3.22 | −3.56 | −0.34† |
| Goodwell–Tahlequah | −2.33 | −2.70 | −0.47† |
| Hooker–Ada | −3.48 | −2.98 | 0.50*‡ |
| Hooker–Miami | −1.12 | −1.19 | −0.07† |
| Hooker–Muskogee | −1.78 | −2.40 | −0.62† |
| Hooker–Newkirk | −2.22 | −2.69 | −0.47† |
| Hooker–Tahlequah | −1.23 | −1.83 | −0.60† |
| Kenton–Ada | −5.61 | −4.84 | 0.77*‡ |
| Kenton–Miami | −3.25 | −3.05 | 0.20† |
| Kenton–Muskogee | −3.91 | −4.26 | −0.35† |
| Kenton–Newkirk | −4.35 | −4.55 | −0.20† |
| Kenton–Tahlequah | −3.36 | −3.69 | −0.33† |
| *Texas* | | | |
| Crosbyton–Blanco | −2.69 | −2.23 | 0.46*‡ |
| Crosbyton–Lampasas | −2.30 | −1.65 | 0.65*‡ |
| Crosbyton–Llano | −2.70 | −2.70 | 0.00† |
| Crosbyton–Mexia | −3.19 | −2.67 | 0.52* |
| Crosbyton–Temple | −3.95 | −3.39 | 0.56*‡ |
| Haskell–Blanco | −0.07 | −0.15 | −0.08 |
| Haskell–Lampasas | 0.32 | 0.73 | 0.41*‡ |
| Haskell–Llano | −0.08 | −0.32 | −0.24† |
| Haskell–Mexia | −0.57 | −0.29 | 0.28† |
| Haskell–Temple | −1.33 | −1.01 | 0.32*‡ |
| Pecos–Blanco | −2.54 | −1.73 | 0.81*‡ |
| Pecos–Lampasas | −2.15 | −1.15 | 1.00*‡ |
| Pecos–Llano | −2.55 | −2.20 | 0.35† |
| Pecos–Mexia | −3.04 | −2.17 | 0.87*‡ |
| Pecos–Temple | −3.80 | −2.89 | 0.91*‡ |
| Stratford–Blanco | −5.89 | −5.20 | 0.69*‡ |
| Stratford–Lampasas | −5.50 | −4.62 | 0.88*‡ |
| Stratford–Llano | −5.90 | −5.67 | 0.23† |
| Stratford–Mexia | −6.39 | −5.64 | 0.75*‡ |
| Stratford–Temple | −7.15 | −6.36 | 0.79*‡ |

In addition, the temperature trends inherent in the data due to other forcings (like increasing $CO_2$ levels) may have dominated over the irrigation effects. This argument is consistent with the findings in Texas and Oklahoma which for the most part indicated a warming of maximum and minimum temperature in the post-45 compared to the pre-1945 period. In the other states (Nebraska, New Mexico, and Kansas, for example) it is apparent that land-use change, introduction of irrigation, and resultant increase of latent energy flux caused the lowering of growing season $GT_{max}$. This study proposes that the regional variations in responses of $GT_{max}$ are partially dependent upon local extent and intensity in adoption of irrigation as well as other climate forcing.

Previously, various sources of biases were discussed in the data and methodology section and noted above. In addition to these, another unknown is the degree of aliasing in the HCN dataset or in other words the degree to which homogenization methods applied in the creation of HCN data may have introduced errors through failure to correctly identify change points or to misrepresent identified change points (DeGaetano, 2006). Moreover, it is unknown to the authors whether data from an irrigated station was unintentionally corrected by using a non-irrigated station data (a vice-versa) as a reference and subsequent impact on results.

The results of this study offer a number of critical messages. *First,* response of temperatures due to land-use change may be more or less difficult to resolve from region-to-region. *Second,* as a result, local- or sub-regional-scale assessment is essential to better understand the influence of land-use change on temperature. This point is also emphasized by Feddema, Oleson, Bonan,

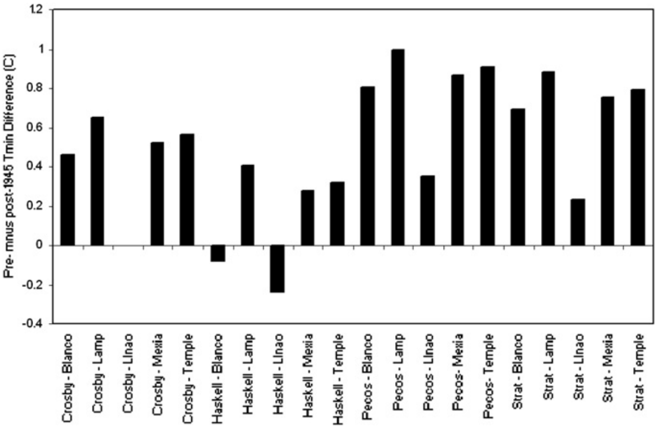

**Fig. 9.** Irrigated (Crosbyton, Haskell, Pecos, and Stratford) minus non-irrigated location growing season mean minimum temperatures for pre- and post-1945 years in Texas.

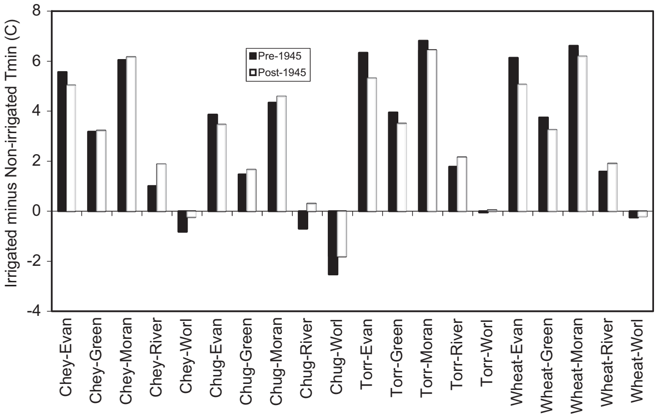

**Fig. 10.** Irrigated (Cheyenne, Chugwater, Torrington, and Wheatland) minus non-irrigated location growing season mean minimum temperatures for pre- and post-1945 years in Wyoming.

Mearns, Washington, et al. (2005). *Third*, the station history needs to be an integral part of this type of analysis to better understand the impacts of instrument exposure on temperature records and should include information on the land-use in the vicinity. *Fourth*, the results for $GT_{max}$ and $GT_{min}$ indicate a complex relationship between land-use, soil moisture, near surface maximum and minimum temperatures which requires further investigation.

In addition, a better understanding of the distance-decay of influence associated with irrigated land-use could be achieved by strategically establishing meteorological stations and data collection, at least for a decade. It is necessary that these stations avoid data bias noted in this paper and reported in the literature. Obviously, observed data needs to be analyzed to identify how and from how far irrigated land-use impacts temperatures. Longer-term data collection could be complemented by field campaigns to fully identify various controls and related pathways that influence temperature (forced by irrigation). Furthermore, complimentary robust high resolution meso-scale modeling study needs to be undertaken to better understand and quantify impacts of distance and irrigation-related temperature changes.

Despite these limitations, results from Nebraska (northeastern part of HPA region) generally agree with other comparable studies and their physical reasoning in a sense that irrigation could cause cooling of $GT_{max}$ and warming of $GT_{min.}$ Kueppers, Snyder, and Sloan (2007) investigated impacts of irrigation on temperatures in California. They have found up to 7.5 °C cooling of August mean maximum temperatures due to irrigation. Likewise, Christy, Norris, Redmond, and Gallo (2006) found lowering of maximum temperature in the irrigated areas of central California during June through August. Total irrigated crop area in California is slightly greater than irrigated corn land-use in Nebraska and thus results are comparable. Kalnay and Cai (2003) and Bonan (1999, 1997) found a cooling trend in maximum temperature during spring, summer, and fall in the Midwest and indicated that overturning of grass lands to agricultural land-use resulted in increased evaporation and decreasing maximum temperature. Thus, findings of these studies are generally in agreement with findings from northeastern region (Nebraska) of the HPA region.

The authors of this study suggest that impacts of land-use change on local and regional temperature can be found in other parts of the world. For example, impacts of the Green Revolution and associated introduction of irrigation in India indicate a cooling during growing season (Roy et al., 2007). We agree with Feddema, Oleson, Bonan, Mearns, Washington, et al., 2005 that global scale averaging would mask the impacts of land-use change on climate because they are highly regional. Based on the results of the current study, we expand on this notion and call for regional-, sub-regional- and local-scale assessment based on observed data for further verification of these modeling results. Analyses at these scales will help to clearly identify geographical variations in the magnitude of the climate system response.

**Table 5**
Composite differences in growing season mean minimum temperatures ($GT_{min}$) of irrigated and non-irrigated during pre- and post-1945 period. Negative sign indicates overall cooling.

| State | Irrigated − non-irrigated pre-1945 $GT_{min}$ (°C) | Irrigated - non-irrigated post-1945 $GT_{min}$ (°C) | Difference |
|---|---|---|---|
| Nebraska | −1.40 | −1.41 | 0.01 |
| Wyoming | 2.90 | 2.89 | −0.01 |
| Kansas | −0.47 | −0.69 | −0.22 |
| Colorado | 8.94 | 8.61 | −0.33 |
| New Mexico | 2.28 | 2.58 | 0.30 |
| Oklahoma | −2.90 | −3.07 | −0.17 |
| Texas | −3.07 | −2.56 | 0.51 |

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