Evidence of enhanced precipitation due to irrigation over the Great Plains of the United States

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[1] At the end of World War II, there was a rapid increase in irrigation over the Ogallala Aquifer in the Great Plains of the United States via groundwater withdrawal, and we hypothesize that this disruption of the local hydrological cycle has enhanced the regional precipitation. We examined station and gridded precipitation observations for the warm season months over and downwind of the Ogallala over the 20th century. Increases in precipitation of 15–30% were detected during July from the easternmost part of the aquifer to as far downwind as Indiana. The timing (1940s, July) and spatial pattern of the precipitation increase are consistent with the history of Ogallala irrigation and mechanisms by which increases in evapotranspiration can affect convection. Additionally, we conducted a vapor tracking analysis and found that evapotranspiration over the Ogallala Aquifer contributes to downwind precipitation and that the contribution is greater when the evapotranspiration is higher. This makes it hydrologically possible that the irrigation development was associated with the observed precipitation increases. Finally, there is no clear evidence that atmospheric circulation changes or modes of internal climate variability increased the July precipitation. Further analysis of the influence of Ogallala irrigation on precipitation will include the controlled analysis of climate model simulations that explicitly include irrigation.

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1. Introduction

[2] Humans have been threatening the sustainability of groundwater storage in the Ogallala Aquifer of the Great Plains since the 1940s, when pumping of groundwater for irrigation began to soar (Figure 1a) [*McGuire*, 2009]. By continually pumping groundwater each year for irrigation, groundwater storage over the Ogallala decreased by about 333 km^3 (8.5%) between pre-development (i.e., before 1950) and 2007 [*McGuire*, 2009]. This has had particularly significant hydrologic impacts over the Texas and Oklahoma panhandles and western Kansas, where groundwater declines have been most significant (Figure 1b). As a result, the amount of surface water available for evapotranspiration (ET) over the Ogallala has approximately doubled between pre-development and the 21st century [*Moore and Rojstaczer*, 2001]. Most of the added surface water from irrigation evaporates rather than runs off or returns to groundwater [*Moore and Rojstaczer*, 2002].

[3] The effect of this human alteration of the natural water cycle on regional precipitation over this area is the subject of this study. We hypothesize that the increase in irrigation over the 20th century resulted in a detectable enhancement of precipitation over the Great Plains. An analysis of long-term precipitation observations and simulations is combined with wind observations and vapor transport analysis to search for the link between irrigation and increases in precipitation over the region.

[4] The mechanisms linking increased irrigation and enhancement of precipitation are most likely related to the effects of increased ET on precipitable water and convection over this region. The possibility of convection being influenced by irrigation is supported by the fact that most irrigation over the Ogallala occurs in July and August (Figure 1c) when more than 80% of precipitation originates from thunderstorms [*Changnon*, 2001]. Convection is associated with the convective available potential energy (CAPE) of the atmosphere, which increases with warmer and moister lower tropospheric conditions. Higher values of CAPE make convection more likely when synoptic conditions are favorable for convection,

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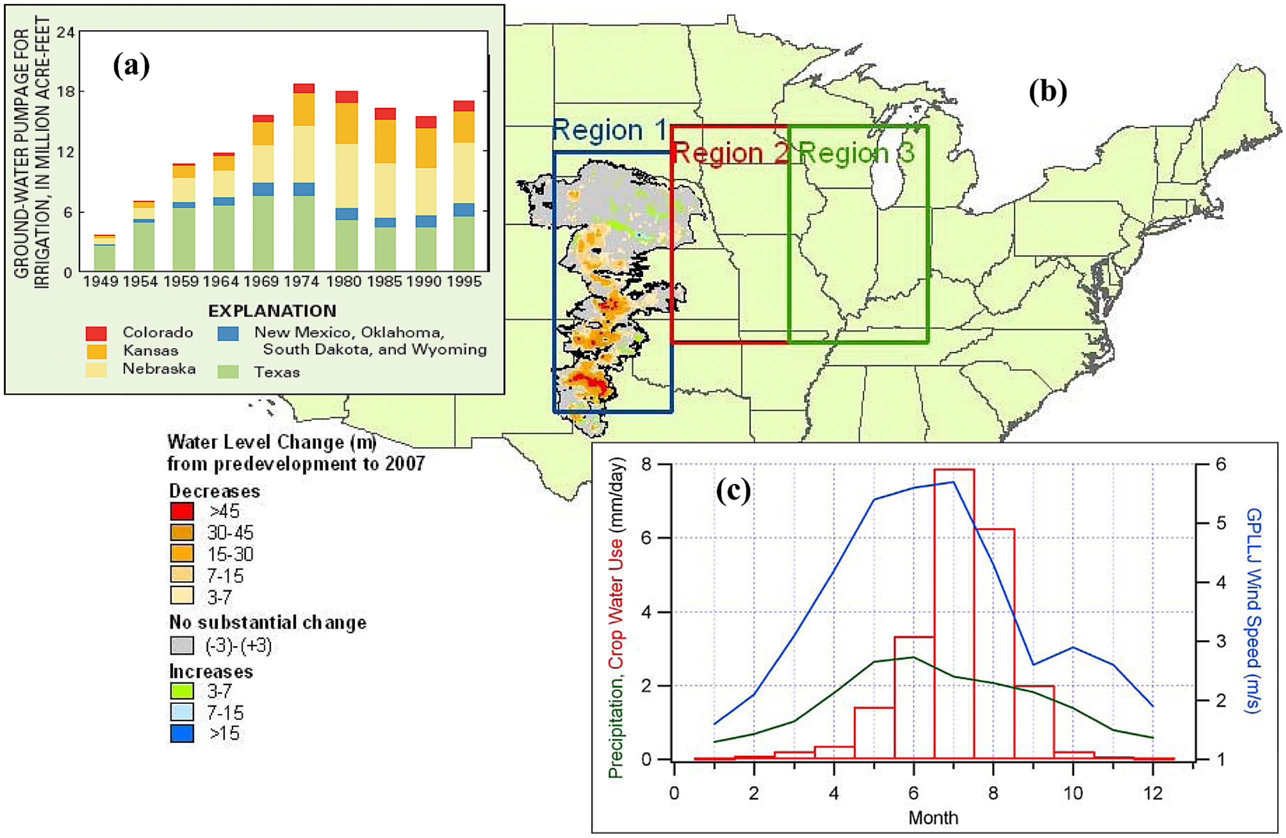

Figure 1. (a) Groundwater pumpage for irrigation from 1949 to 1995 in the Great Plains states [*McGuire et al.*, 2003], (b) outline of Ogallala Aquifer and groundwater level changes from pre-development (pre 1950) to 2007 and the 3 regions investigated in this study (Region 1: 104°W–98°W, 33°N–44°N; Region 2: 98°W–92°W, 36°N–45°N; Region 3: 92°W–85°W, 36°N–45°N), and (c) monthly crop water use for the major crops grown in the Great Plains, mean monthly precipitation averaged over Region 1 for the period 1900–2000, and the mean annual cycle of the Great Plains low-level jet (GPLLJ) for 1979–2002 (area averaged meridional winds in the region 100°W–95°W, 25°N–35°N from NARR [*Weaver et al.*, 2009]).

or can be the difference between convection and no convection if synoptic conditions are borderline favorable [*Barnston and Schickedanz*, 1984; *De Ridder and Gallée*, 1998]. It follows that if irrigation influences lower troposphere temperature and moisture, it will impact CAPE and therefore convective precipitation. Numerous modeling studies have shown that increased surface moisture from irrigation leads to enhanced ET and atmospheric moisture content over irrigated regions worldwide [*Boucher et al.*, 2004; *Gordon et al.*, 2005]. It has also been shown that the increased latent heat flux and increased cloud cover associated with irrigation cool the surface, with a particularly strong effect on daily maximum temperatures (of at least 2°C in many regions) [*Barnston and Schickedanz*, 1984; *Sacks et al.*, 2009; *Lobell and Bonfils*, 2008; *Lobell et al.*, 2008].

[5] The above effects of irrigation on the lower troposphere temperature and moisture have competing effects on CAPE directly over irrigated land. More specifically, the cooler surface temperatures induced by irrigation reduce CAPE while the increased moisture increases CAPE. However, it is logical that downwind of the irrigated land, surface temperatures are not cooled by local increases in latent heat flux or clouds, and added moisture from the irrigated region is transported in, only increasing CAPE. This would promote irrigation-induced precipitation enhancement that is mainly downwind of the irrigated fields. This theory is supported by previous studies, which suggest that deep cumulus convection can be inhibited over moist soils with high latent heat flux (such as irrigated fields) due to a decreased boundary layer height [*Pielke*, 2001; *Ek and Holtslag*, 2004; *Findell and Eltahir*, 2003]. Furthermore, modeling studies on the effects of irrigation on precipitation have shown that precipitation enhancement caused by irrigation occurs in regions that are quite distant from the irrigated fields [*Segal et al.*, 1998]. The formation of mesoscale circulations initiated by surface soil moisture heterogeneity [*Hammer*, 1970; *Eltahir and Bras*, 1996; *Avissar and Liu*, 1996; *Pielke et al.*, 1997; *Georgescu et al.*, 2003] is a mechanism by which irrigation could promote an enhancement of precipitation closer to the boundaries of irrigated land. In summary, precipitation enhancement caused by irrigation is likely to be strongest from the boundaries of the Ogallala Aquifer to downwind regions. We analyze precipitation both over and downwind of the Ogallala to search for such precipitation enhancement.

[6] Observational studies over the past several decades have been equivocal in detecting a response in precipitation

to irrigation over numerous regions, including the Ogallala Aquifer. For example, two studies focused on the Columbia River Basin in the 1970s led to contradictory results on the detection of enhanced observed precipitation in response to irrigation increases; *Eddy et al.* [1975] detected enhanced precipitation both upwind and downwind of the irrigated region, while *Fowler and Helvey* [1975] did not. Later studies focused over the Ogallala Aquifer did not agree on an observed precipitation response to irrigation either; while *Barnston and Schickedanz* [1984] detected ~20% increases in June precipitation associated with irrigation over the period 1930–1970 in the Texas panhandle, *Moore and Rojstaczer* [2001] found no such signal over either the same region or Nebraska and Kansas for the period 1950–1982. A third study focused in the Ogallala Aquifer detected an enhancement of summertime precipitation 90 km east of a heavily irrigated part of the Texas panhandle in 1996 and 1997 [*Moore and Rojstaczer*, 2002].

[7] Some caveats associated with these previous observational studies are that their analyses were restricted to short time periods, inappropriate time periods, small domains, or a combination thereof. For example, the time period 1950–1982 used to study the irrigation response in the Great Plains by *Moore and Rojstaczer* [2001] may have failed to show a signal because irrigation was already increasing dramatically over the region by 1950 [*McGuire*, 2009] or because a 33-year period is too short for statistically significant trends to be detected. Similarly, the study of only 1996 and 1997 in the Texas panhandle by *Moore and Rojstaczer* [2002] did not provide a large enough sample of data to make strong and convincing conclusions. Additionally, most of the previous observational studies failed to search for the precipitation response to irrigation far beyond the boundaries of the irrigated region. As already discussed, an irrigation signal in precipitation is likely to occur downwind of the immediate irrigated region. We address these shortcomings by analyzing an extensive precipitation observation data set that covers the entire 20th century and extends well beyond the boundaries of the Ogallala Aquifer.

[8] While observational studies have been equivocal, modeling studies have been fairly convincing in showing that irrigation (or wetter soil) tends to enhance precipitation. *Koster et al.* [2004], using an ensemble of atmospheric general circulation models, showed that variations in soil moisture can explain more than 10% of the precipitation variability over the Great Plains. This suggests that the surface wetness may have strong influences on precipitation in the region. *Sacks et al.* [2009], using a coupled land-atmosphere general circulation model, showed that globally, land-averaged JJA (June–July–August) precipitation increased by 1.27% between a control and realistic irrigation experiment. *Segal et al.* [1998] used a numerical model to test the effects of irrigation over the United States on precipitation during various 7-day weather patterns (i.e., floods, dry spells, and normal); in all cases, irrigation increased precipitation by as much as 6 mm or more in areas that are distant from irrigated fields and associated with large scale regions of maximum precipitation over the 7-day periods. In summary, modeling studies agree that irrigation can enhance precipitation though observational studies give equivocal results. This suggests that irrigation-induced precipitation enhancement may require further observational investigation.

[9] In this study, several analyses were performed in search of evidence of irrigation enhanced precipitation over and downwind of the Ogallala. In section 2, we investigated the history and seasonal pattern of irrigation to provide insight as to when to expect precipitation enhancement caused by irrigation. In section 3.1, 20th century precipitation observations were analyzed over three regions (Figure 1b) using data from 865 precipitation stations that have continuous record from the 1940s to 1980s. The three regions selected represent local (Region 1), immediately downwind (Region 2), and far downwind (Region 3) locations from the Ogallala Aquifer moisture source. In section 3.2, we assessed the contribution of Ogallala ET to local and downwind precipitation using a Lagrangian tracer study of atmospheric vapor transport based on the North America Regional Reanalysis (NARR) [*Mesinger et al.*, 2006]. Finally, in section 3.3, we investigated other mechanisms besides irrigation that might have caused observed 20th century precipitation changes. In part of this investigation, observations were compared with global general circulation climate model (GCM) simulations over the 20th century that do not include irrigation, to see if simulated changes in precipitation mainly associated with atmospheric circulation changes are consistent with observed precipitation changes.

2. Irrigation History and Seasonal Pattern

[10] Knowledge of the history of irrigation over the Ogallala is important because it provides information about when to search for precipitation changes associated with irrigation. Between the 1930s and 1980s, the area of irrigated land over the Great Plains increased dramatically from less than 7,500 km^2 to more than 60,000 km^2 [*Moore and Rojstaczer*, 2001]. In particular, the 2009 report from the U.S. Geological Survey on groundwater storage over the Great Plains showed that the largest expansion of irrigation occurred between 1949 and 1974, when the groundwater withdrawals increased by 475% [*McGuire*, 2009] (see also Figure 1a). After 1974, water withdrawal stopped increasing and remained comparable to 1974 levels through the early 21st century [*McGuire*, 2009]. Thus, in this study, emphasis is placed on shifts in precipitation from the period before the rapid increase in irrigation (1900–1950) to that after irrigation had already taken hold of the region (1950–2000).

[11] It is also important to understand the seasonal pattern of irrigational water use across the region because the effect of irrigation on precipitation, if any, is likely to be strongest during the most heavily irrigated time of year. As an indication of the seasonal pattern of the need for irrigation, which is likely proportional to actual irrigation [*Colaizzi et al.*, 2009], we quantified the monthly crop water use and precipitation over the Ogallala. For the monthly crop water use, we used two sets of data. First, the irrigated acreage of the most prevalent crops (corn, cotton, sorghum, soybean, and wheat) grown across the eight states encompassing the Ogallala Aquifer (Colorado, Kansas, Nebraska, New Mexico, Oklahoma, Texas, South Dakota, and Wyoming) were obtained from the U.S. Department of Agriculture 2002 Census of Agriculture (http://www.agcensus.usda.gov/Publications/2002/index.asp). The 2002 Census was used because it has the best combination of data completion and representation of post-irrigation crop distribution over the Great Plains. Second,

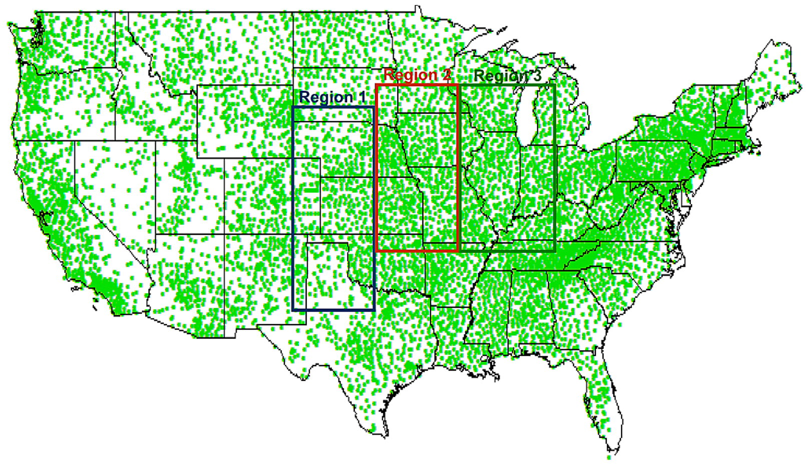

Figure 2. Precipitation stations with continuous record for the period 1940–1980 used for analysis in this paper.

characteristic seasonal water use data for the five crops were obtained from regional agricultural documents [*Rogers*, 1997a, 1997b, 2007; *New*, 2004] (also New Mexico climate center cotton irrigation scheduling (http://weather.nmsu.edu/nmcrops/cotton/cottonirrschpro.htm)). The overall seasonal cycle of crop water use was obtained by weighting the water use of each crop with its irrigated acreage and then summing over the five crops, for each month. The result is shown in Figure 1c (red bars), together with the long-term (1900–2000) mean precipitation averaged over Region 1 (green curve).

[12] Figure 1c suggests that the Ogallala region as a whole has a need for irrigation between June and September, when potential crop water use exceeds precipitation. However, the greatest water deficits occur in July and August, suggesting the greatest need for irrigation, while water deficits in June and September appear relatively small. Recent modeling efforts of United States irrigation reveal that the effect of Ogallala irrigation on local ET is greatest in July and August, consistent with the results shown here [*Ozdogan et al.*, 2010]. Assuming that the seasonal increase in irrigation over the 20th century is proportional to the present-day seasonal pattern of irrigation need (Figure 1c), precipitation increases associated with Ogallala irrigation would most likely be detected in July and August. Here, we analyze precipitation data from May through September, where the irrigation signal is mostly anticipated in July and August, while little or no irrigation signal is expected in May, June, and September.

3. Results and Discussion

3.1. Precipitation Observations Analysis

[13] Station monthly precipitation data were obtained from the National Climatic Data Center monthly surface data archive (http://www.ncdc.noaa.gov/oa/climate/climatedata.html#monthly). Station locations for the contiguous U.S. are shown in Figure 2. For all plots and calculations involving regional precipitation in this paper, the area-averaged precipitation was computed by taking the arithmetic average of the precipitation from all stations in the region. The station density over the study domain (Figure 2) was assumed large enough that a more sophisticated averaging procedure was unnecessary, and would not fundamentally change the results. The area-averaged precipitation over each of the three regions (Figure 1b) is plotted in Figure 3 for May through September, together with the number of stations reporting. The number of stations increased by fivefold from 1930 to 1931, but stayed rather constant over the irrigation ramping up period (1940–1980, Figure 1a) and hence will not affect the calculated regional precipitation changes over the period of irrigation expansion. The precipitation in Figure 3 is shown as the 5-year moving average to better discern long-term variations.

[14] Large inter-annual variability dominates the time series in all regions and months. However, a step-like increase in precipitation is perceptible in Region 3 during July, where the mean of the inter-annual oscillations appears higher after 1950. There also appears to be an increase in precipitation in Region 2 during July in the 1940s, with relatively high precipitation maintained through the end of the century. In both cases, the timing of the precipitation increase (1940s) coincides with the start of rapid expansion of irrigation after World War II [*McGuire*, 2009]. To more quantitatively assess the changes in precipitation between the periods 1900–1950 and 1950–2000 (periods that represent pre- and post-irrigation), a two sample Student t test was applied to the mean precipitation for the two periods. Table 1 shows the change in area-averaged time-mean precipitation between the two periods for each month and region (expressed as an amount and percentage), along with the significance of the change based on a two-tailed test. The 20.9% precipitation increase in Region 3 during July was the only significant change of any region or month at a significance of 5%. Although the precipitation increase in Region 2 during July was not statistically significant at the 5% level, the 14.1% increase was substantial and represents the second largest precipitation change of any region or month investigated.

[15] To strengthen the results that a statistically significant change in precipitation occurred during the middle of the 20th century in Region 3 during July, a statistical change point analysis was applied to the data. The non-parametric Pettitt test [*Pettitt*, 1979] is commonly used to search for a statistically significant abrupt change in the time series of a variable

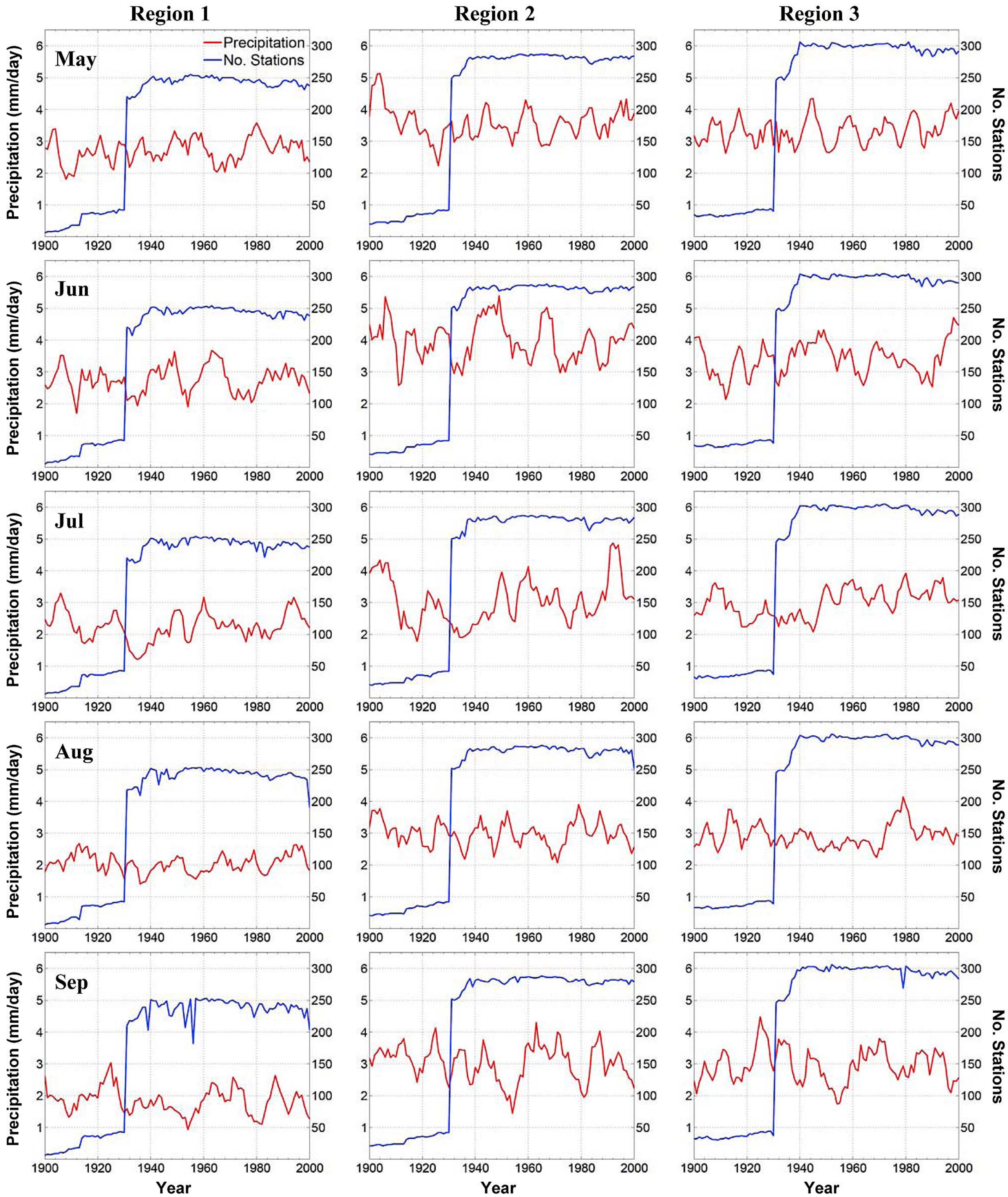

Figure 3. Monthly precipitation and the number of stations reporting for (left to right) the three regions (Figure 1b) and (top to bottom) five summer months analyzed in this paper. Over the period of continuous record, there was a maximum of 258 stations in Region 1, 291 in Region 2, and 316 in Region 3. The precipitation was area-averaged over each region, then smoothed with a 5 year running average prior to being plotted.

Table 1. Results of Statistical Tests on Observed Precipitation Changes Over the 20th Century[a]

	t Test 1900–1950, 1950–2000		Pettitt Test		*t* Test 1900 to Change Point, Change Point to 2000	
Region and Month	Change (mm/day)	Sig.	Change Point (year)	Sig.	Change (mm/day)	Sig.
Region 1						
May	+0.16 (+6.1%)		1934			
June	+0.05 (+1.7%)		1940			
July	+0.22 (+10.1%)		1957			
August	−0.00 (−0.1%)		1985			
September	−0.13 (−6.6%)		1927			
Region 2						
May	−0.03 (−0.7%)		1941			
June	−0.18 (−4.4%)		1951			
July	+0.40 (+14.1%)		1909			
August	+0.00 (+0.0%)		1933			
September	−0.19 (−6.0%)		1927			
Region 3						
May	+0.07 (+2.2%)		1941			
June	+0.03 (+0.9%)		1936			
July	+0.57 (+20.9%)	S	1947	S	+0.64 (+24.2%)	S
August	+0.04 (+1.3%)		1971			
September	−0.13 (−4.3%)		1938			

[a]Tests were applied to station precipitation that was averaged over each region. The change in mean precipitation from the earlier to later period specified for the *t* tests is given. Positive changes indicate that the later period was wetter. The significance column (Sig.) indicates if the change is significant at the 5% (S) level based on a two-tailed test. The second *t* test using the change point determined by the Pettitt test [*Pettitt*, 1979] was only carried out if the results of the Pettitt test were statistically significant at the 5% level.

when the timing of the change is not assumed a priori. The Pettitt test has been successfully used to detect changes in hydrological data [e.g., *Aka et al.*, 1996] and therefore its use in the present study is appropriate. Table 1 shows the change point in precipitation for the period 1900–2000 detected by the Pettitt test, as well as the significance level of the change point for all of the regions and months investigated. The only statistically significant change point at the 5% level was detected at 1947 in Region 3 during July. A subsequent two sample *t* test was applied to the July precipitation for the periods 1900–1947 and 1947–2000 in Region 3 and again showed a significant precipitation increase at the 5% level based on a two-tailed test (rightmost column in Table 1). The results of the Pettitt test strongly confirm that there was an unusual jump in precipitation halfway through the 20th century in Region 3 during July. However, the perceptible increase in July precipitation in Region 2 (Figure 3) was not detected from the Pettitt test, as the sharp decrease in the beginning of the 20th century was larger (Table 1).

[16] In the previous discussion, we only found a statistically significant increase in precipitation in Region 3 during July, despite the fact that we were also expecting a significant increase in Region 3 during August and in Region 2 during July and August. This raises the issue of field significance [*Livezey and Chen*, 1983], or whether or not one out of the four *t* tests being statistically significant is collectively significant. In other words, what is the likelihood that out four individual *t* tests, at least one of them would be statistically significant at the 5% level if there was really no change in precipitation between the first and second halves of the 20th century? If the likelihood of this is greater than 5%, then the four tests are not field significant at the 5% level. Assuming that the individual statistical tests are independent, the test for field significance is a simple binomial calculation [*Wilks*, 1995]. The assumption of independence will give a lower limit on the p-value associated with the field significance [*Wilks*, 1995]. Thus, if the results are not field significant when independence is assumed, no further analysis assuming spatial correlation is necessary because the results will be even less significant if spatial correlation is accounted for [*Wilks*, 1995]. The results of the field significance test applied here assuming independence indicates that the collective observed precipitation changes (Table 1) for the four region/month combinations (Region 2 July, Region 2 August, Region 3 July, Region 3 August) are not field significant at the 5% level. More specifically, there is an 18.5% chance that at least one out of the four statistical tests would be significant at the 5% level if there was really no change in the precipitation. This indicates that we cannot rule out the possibility that the one observed significant precipitation increase in Region 3 during July happened by chance due to the natural variability of annual precipitation.

[17] The maps in Figure 4 illustrate the spatial patterns in the observed precipitation changes between the periods 1900–1950 and 1950–2000. These plots are based on gridded station data for North America at 1° × 1° lat-lon resolution, a data set developed at Rutgers University [*Dyer and Mote*, 2006]. Differences in mean precipitation between the two periods are plotted for May through September, overlaid on the mean monthly 850-mb winds obtained from NARR. The winds are plotted as a first indicator of the direction of moisture transport from the Ogallala Aquifer source (although moisture transport is investigated in greater depth in the next section). Focusing on July, precipitation increased by 15–30% in a broad region from the eastern part of the Ogallala region (Region 1) to the furthest downwind region (Region 3). Despite the lack of statistical significance for the increase in Region 2 precipitation (Table 1), the maps in Figure 4 show that the precipitation increase in Region 2 is substantial, physically meaningful, and that it is continuous with the

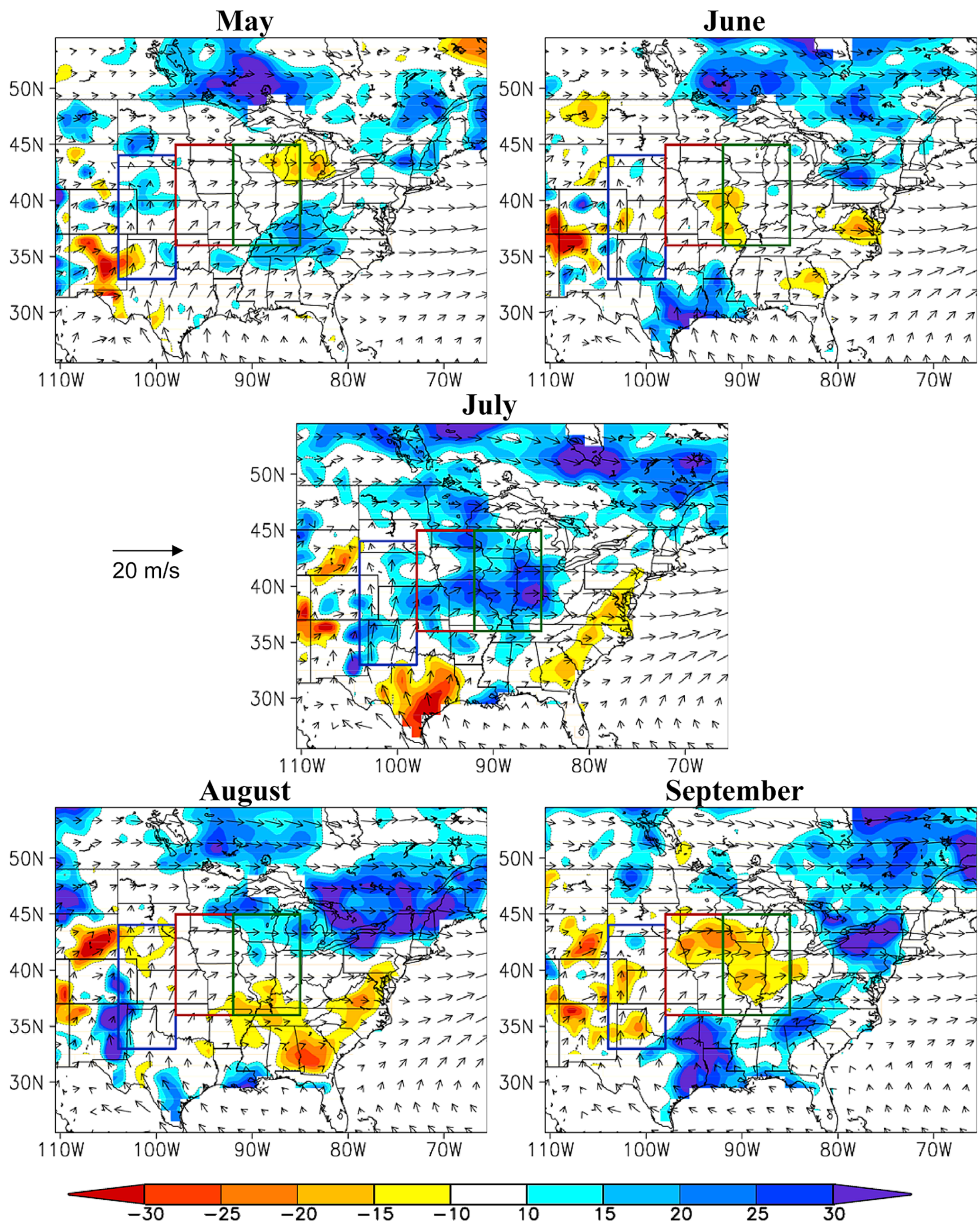

Figure 4. Spatial patterns of the change in mean precipitation (%) between the periods 1900–1950 and 1950–2000 derived from gridded observations, for the five summer months analyzed in this paper. Precipitation observations are missing over Mexico and the ocean. The vectors indicate the 1979–2001 mean 850 mb winds (m/s) obtained from NARR for the respective months. The three study regions are outlined for reference.

statistically significant precipitation increases further downwind. The 850-mb wind blows from the southern part of Region 1 through Region 2 and Region 3, and is nearly in line with the band of observed precipitation increase stretching from the easternmost part of Region 1 through Region 3. This orientation of precipitation increase with respect to the prevailing wind provides additional evidence that at least part of the observed July precipitation increases could have been associated with increased moisture transport from the Ogallala due to irrigation.

[18] In summary, the July observations are supportive of the hypothesis that irrigation may have led to precipitation enhancement downwind of the Ogallala Aquifer. However, there was no change in precipitation in the region during

August (Table 1), a month when irrigation over the region is also substantial (Figure 1c). One possible explanation why irrigation might not enhance downwind precipitation in August is that the large scale atmospheric dynamics that are conducive to precipitation over the region are weaker in August, such that the increased moisture from irrigation is not enough to trigger enhanced convection. This hypothesis is supported by a study on the low-level jet, a lower atmospheric wind feature that favors convection in the Great Plains [*Weaver et al.*, 2009]. *Weaver et al.* [2009] showed that the low level jet peaks in May through July and begins to decline rapidly in August (blue curve in Figure 1c). Perhaps the weakening of the low level jet by August reduces the available moisture and necessary thermodynamic conditions for convection enough that increased moisture export from the Ogallala does not make a difference. Another possible explanation for no August precipitation enhancement is that the greater July precipitation downwind of the Ogallala in the later 20th century moistened the surface, enhancing local evapotranspiration and causing surface cooling [*Barnston and Schickedanz*, 1984; *Sacks et al.*, 2009; *Lobell and Bonfils*, 2008; *Lobell et al.*, 2008]. This would have made conditions less favorable for convection in August in the second half of the 20th century [*Barnston and Schickedanz*, 1984; *De Ridder and Gallée*, 1998; *Pielke*, 2001; *Ek and Holtslag*, 2004; *Findell and Eltahir*, 2003]. Despite the evidence that an irrigation induced precipitation response would be weaker in August, the question remains of how much weaker the response would be. This is a topic that demands further quantification with model simulations incorporating irrigation moisture and the mechanisms associated with Great Plains precipitation.

3.2. Lagrangian Tracing of Vapor Sources

[19] To assess the ability of vapor transport from the Ogallala Aquifer to influence local and downwind precipitation, we performed a more detailed and quantitative investigation of the physical link between Ogallala ET and downwind precipitation. While the NARR 850-mb winds shown in Figure 4 suggest that ET from Region 1 is transported into Region 2 and Region 3, a remaining question is: how much does Region 1 ET actually contribute to the Region 2 and Region 3 precipitation, particularly during July? And more importantly, how does the contribution of Region 1 ET to Region 2 and Region 3 precipitation vary under different soil wetness conditions in Region 1? The answer to these questions would provide insight as to how likely the observed precipitation increases during July discussed in the previous section may have been associated with increased ET from the Ogallala irrigation.

[20] *Dominguez et al.* [2009] showed that ET from the four-corner states (Utah, Colorado, Arizona, and New Mexico), a region with its summer precipitation strongly influenced by the North American Monsoon (NAM), has pronounced and far-reaching effects on downwind precipitation. In particular, they showed that ET in July and August could contribute to as much as 40% of the precipitation downwind during an intense NAM year when the soil moisture in the four corner states is relatively high, whereas ET is limited and has little influence downwind during a weak NAM year. These results demonstrate that land surface fluxes of water and energy upwind of an atmospheric transport pathway can influence the downwind fluxes at regional to continental scales.

[21] We performed a similar analysis to that of *Dominguez et al.* [2009] with the moisture source region being the Ogallala Aquifer (Region 1). The amount of precipitation falling over North America originating as ET from Region 1 was calculated with the Dynamic Recycling Model (DRM) [*Dominguez et al.*, 2006]. The DRM estimates source and sink regions of evapotranspired moisture. As with all bulk recycling models, it is derived from the conservation equation for water vapor of recycled origin. The DRM uses a Lagrangian coordinate system that enables following the trajectory of advected moisture. The model also provides an expression for the local recycling ratio, defined as the fraction of precipitation falling in one specific grid cell originating as ET from within a specified subregion (in this case Region 1).

[22] The DRM used here requires gridded mean and transient values of specific humidity and zonal and meridional winds in the vertical column, as well as ET and precipitation estimates. Daily derived variables from the NARR for July over 1985–2006 were used for these inputs. The NARR improves upon earlier global reanalysis products, particularly in terms of hydrologic modeling, because it assimilates the observed precipitation. Unfortunately, land surface observations such as soil moisture and ET are extremely limited, and are currently not assimilated into NARR. Therefore, ET in NARR is model-estimated and may have significant uncertainty [*Nigam and Ruiz-Barradas*, 2006]. However, NARR is the only gridded data set that provides high resolution and dynamically consistent ET, precipitation, winds, and humidity for multidecadal studies over North America, and is therefore the best data available.

[23] In this analysis, the difference in contribution of Region 1 ET to local precipitation between low ET years and high ET years in Region 1 is analyzed for the period 1985–2006 over the United States. During low Region 1 ET years, there is a vapor shortage similar to that without irrigation, and during high Region 1 ET years, vapor fluxes are greater. Therefore, the difference in Region 1 ET between low and high years is analogous to the difference in Region 1 ET between pre- and post-irrigation, respectively. Any number of factors affecting ET over Region 1 could be responsible for the difference between the low and high ET years investigated here. Because the time period analyzed (1985–2006) occurs during a time when irrigation over the Ogallala region was rather stable (Figure 1a), the difference between low and high ET years was unlikely to be associated with irrigation itself, and more likely to be associated with the local precipitation, which could have been influenced by any number of factors. Figure 5 shows the time series of July Region 1 ET for the period 1985–2006. High ET years were selected as those during which the Region 1 ET was greater than one standard deviation above the mean, and low ET years were selected as those during which Region 1 ET was lower than one standard deviation below the mean. The selected high Region 1 ET years were 1987, 1992, 1993, 1995, and 1999, while the low ET years were 1990, 2002, and 2006.

[24] The July precipitation originating as ET from Region 1 was calculated over the entire United States for the average of the high Region 1 ET years and the low Region 1 ET years using the DRM. Figure 6 shows the results of this

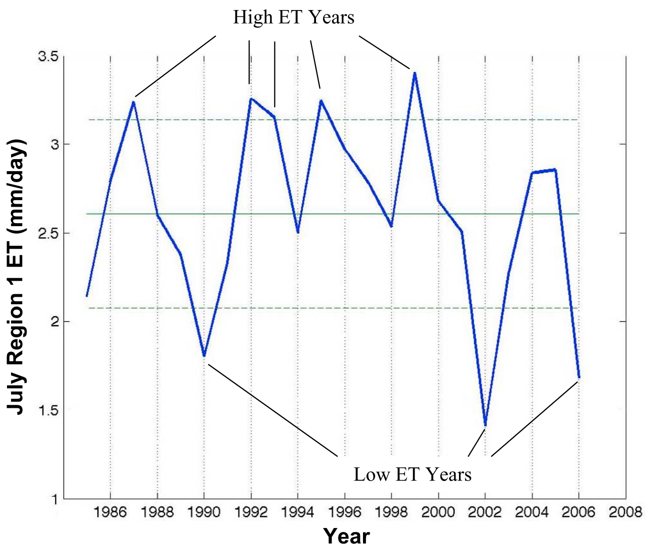

Figure 5. July ET from Region 1 (Figure 1b) derived from NARR. The solid horizontal line shows the 1985–2006 mean, while the dashed horizontal lines indicate one standard deviation above and below the mean. Years in which ET was more than one standard deviation from the mean are labeled and were used for the analysis in Figure 6.

analysis. It is clear that when the ET from Region 1 is high, precipitation originating from Region 1 ET is more intense and extends further downwind of the Ogallala region than when Region 1 ET is low. Indeed, ET from Region 1 contributes to as much as 0.5 mm/day (more than 6% of local total precipitation) in areas that are within and even to the east of the three regions studied in this paper during high ET years. The rightmost panels in Figure 6 more clearly show the difference in precipitation originating from Region 1 ET between the high and low ET years. In particular, the precipitation contribution from Region 1 ET is approximately 0.3–0.5 mm/day (or 2–6% of local total precipitation) greater during high Region 1 ET years over large portions of Region 2 and Region 3. The area-averaged precipitation difference between high and low Region 1 ET years is 0.32 mm/day over Region 2 and 0.22 mm/day over Region 3. The most intense precipitation difference occurs in a region stretching from the northeastern part of Region 1 through most of Region 2, and ending in the northwestern part of Region 3.

[25] To statistically assess the relationship between Region 1 ET and precipitation originating as Region 1 ET for all years between 1985 and 2006, a scatterplot and linear regression analysis was conducted on the area-averaged precipitation originating as Region 1 ET and the Region 1 ET itself for the three regions. This analysis (Figure 7) confirms that there is a positive correlation between Region 1 ET and precipitation originating as Region 1 ET for all three regions. In other words, the contribution of Region 1 ET to precipi-

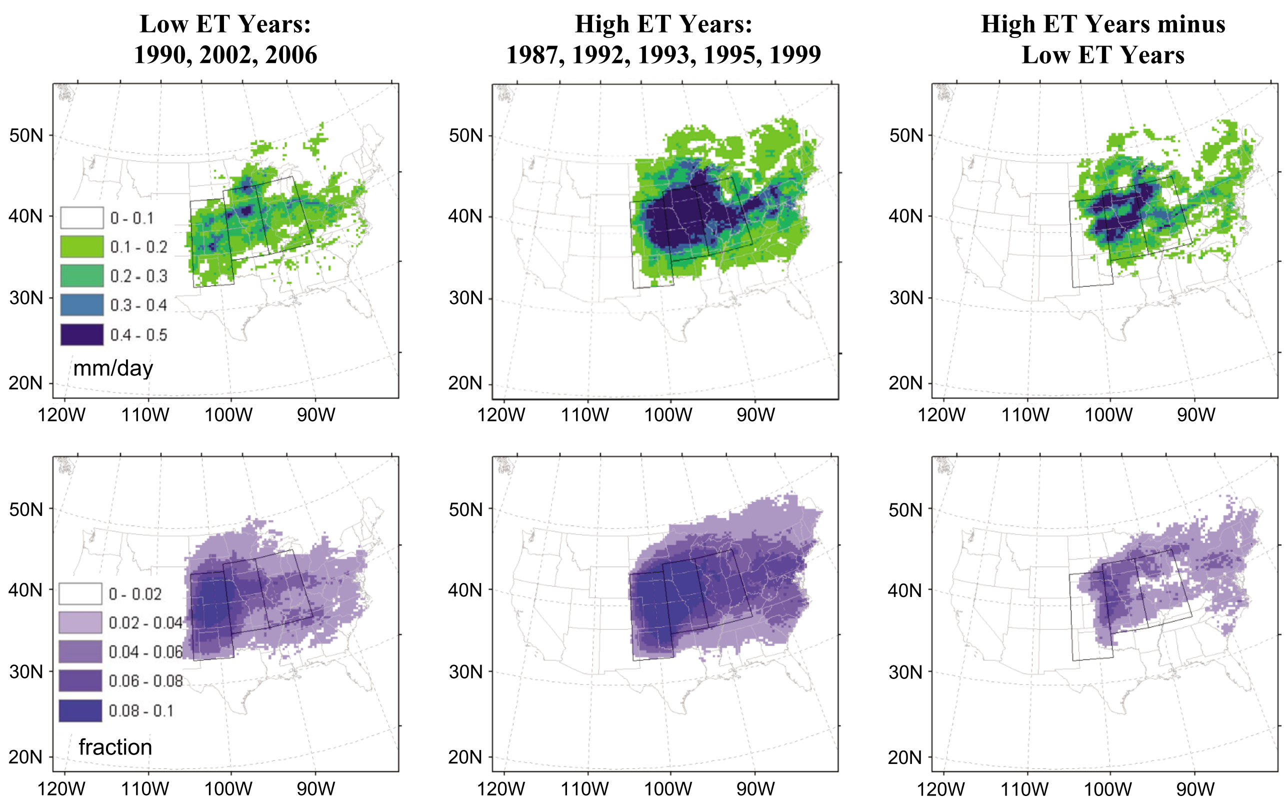

Figure 6. Spatial distribution of average July precipitation originating as Region 1 ET during (left) low ET years and (middle) high ET years. (right) The difference between high and low ET years. See the text for details about the calculations. (top) The precipitation as an amount, and (bottom) precipitation as a percentage of local total precipitation. The three study regions are outlined for reference.

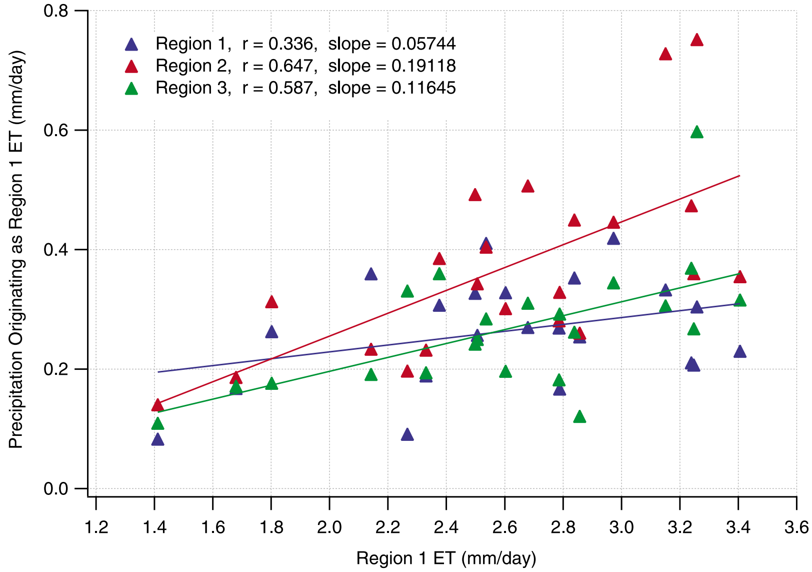

Figure 7. July precipitation amount originating as Region 1 ET as a function of Region 1 ET. All years from the period 1985–2006 are plotted for the three regions (Figure 1b). The Pearson correlation coefficient, *r*, and the slope of a least squares linear regression were calculated from the data in each region.

tation is larger when Region 1 ET is higher. The response of precipitation to Region 1 ET is strongest for Region 2, indicated by the greatest slope and correlation coefficient of the three regions (Figure 7), followed by Region 3 then Region 1.

[26] The results from the vapor tracking analysis confirm that increased ET from Region 1 indeed leads to greater precipitation originating as Region 1 ET during July, particularly just downwind of the region. This suggests that the increase in irrigation during the 20th century over the Ogallala Aquifer could have had a similar effect on precipitation. The increase in total precipitation seen in the 20th century observations during July was greatest in Region 3, while the greatest increase in precipitation originating from Region 1 ET between high and low ET years was in Region 2. This inconsistency makes it unlikely that all or most of the observed July Region 3 precipitation increases could have been related to irrigation alone and that other processes affecting precipitation were important (discussed in the next section). Nonetheless, the observations do show an increase in precipitation downwind of the Ogallala from the easternmost part of Region 1 through Region 3, which is at least qualitatively consistent with the increased precipitation originating from Region 1 ET between high and low ET years shown here.

3.3. Other Potential Causes of 20th Century Precipitation Changes

[27] The question still remains as to how big a contribution (if any) irrigation actually made to the observed precipitation increases downwind of the Ogallala in July. The analysis of observations is not a controlled experiment, where a number of factors (e.g., greenhouse gases, sea surface temperatures, modes of internal climate variability, irrigation, etc.) can affect regional precipitation. Separating the response of irrigation from other factors in precipitation observations is nearly impossible, and conducting a controlled climate model experiment that includes irrigation may be the only way to isolate the response of irrigation on precipitation. While running climate model simulations with and without irrigation is beyond the scope of this study, an attempt is made in this subsection to investigate several other potential factors, aside from irrigation expansion, that may have contributed to the observed July precipitation increases shown earlier.

[28] One potential factor is changes in large scale atmospheric circulation over the 20th century that were forced by changes in sea surface temperatures (SSTs) or atmospheric composition. While current generation GCMs may not be able to reliably simulate summertime convective precipitation due to their coarse resolutions [*Iorio et al.*, 2004], they may provide some insight as to how changes in atmospheric circulation over the 20th century affected large scale precipitation in the absence of irrigation. Here we compare the precipitation observations with 20th century GCM simulations from the CLIVAR International Climate of the Twentieth Century Project (C20C) [*Folland et al.*, 2002]. The models were forced with observed SSTs [*Rayner et al.*, 2003] and observed radiative forcing, but not with any information about irrigation or land use changes. The three models used in this study are described in Table 2. Monthly precipitation output was available for the time periods 1869–2002 for the HadAM3, 1902–2006 for the NSIPP-1, and 1870–1999 for the AM2.1.

[29] In Figure 8, the C20C GCM simulations are compared with observations for Region 3 during July, the region and month showing the most significant increase in precipitation over the 20th century. Precipitation is expressed as an anomaly with respect to the 1910–1945 mean of the observations. The observational mean was used to eliminate biases in model variability caused by biases in model mean precipitation. From Figure 8, it is quite clear that the models do not show the same increase in precipitation during the

Table 2. GCMs From Which 20th Century Simulations are Compared With Observations

Modeling Group	Model	Resolution (Latitude × Longitude, Vertical Levels)	Ensemble Members	References
Hadley Centre for Climate Research and Prediction	HadAM3	2.5° × 3.75°, L19	6	*Pope et al.* [2000]
NASA Goddard Space Flight Center	NSIPP-1	3° × 3.75°, L34	8	*Bacmeister et al.* [2000], *Pegion et al.* [2000], *Schubert et al.* [2002]
NOAA Geophysical Fluid Dynamics Laboratory	AM2.1	2° × 2.5°, L24	10	*Delworth et al.* [2006]

middle of the 20th century as the observations. This is true for the ensemble averages of all models, as well as the individual ensemble members of all of the AM2.1 and HadAM3 simulations. Indeed, many of these simulations show substantial drying trends over the course of the 20th century. For the NSIPP-1, it appears that a few ensemble members approach the observations toward the later 20th century.

[30] To more quantitatively assess the changes in precipitation between the first and second halves of the 20th century in the GCM simulations, particularly for the NSIPP-1, we conducted a two sample *t* test (analogous to the leftmost column in Table 1) for each ensemble member of each GCM. In this analysis (not shown), five out of the eight NSIPP-1 ensemble members showed an increase in precipitation between the periods 1902–1950 and 1950–2000 in Region 3 during July, but none of these increases were statistically significant at the 5% level based on a two-tailed test. All of the ensemble members of the AM2.1 and HadAM3 showed precipitation decreases in Region 3 during July between similar time periods, some of which were actually statistically significant at the 5% level. As for Region 2 during July, when observed precipitation also increased, only one ensemble member of the NSIPP-1 showed an increase in precipitation between the periods 1902–1950 and 1950–

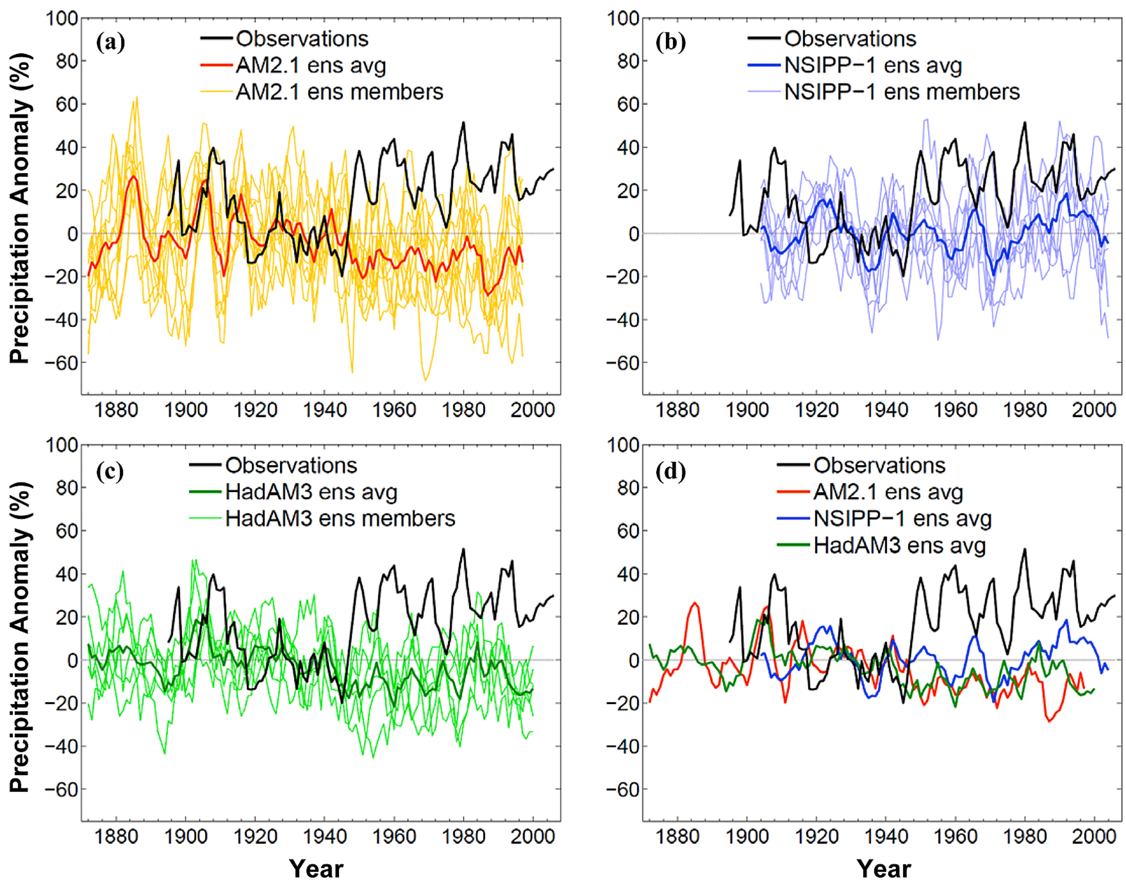

Figure 8. Comparison of July precipitation between station observations and the individual ensemble members and ensemble average from the (a) AM2.1, (b) NSIPP-1, (c) HadAM3, and (d) all C20C simulations. The precipitation is expressed as an anomaly with respect to the 1910–1945 observations mean. The precipitation was averaged over Region 3 (Figure 1b), then smoothed with a 5 year running mean prior to being plotted.

2000, but this was not statistically significant at the 5% level. All other ensemble members of every GCM showed precipitation decreases in Region 2 during July, many of which were statistically significant at the 5% level.

[31] The results from the previous analysis indicate that GCMs generally do not show an increase in precipitation over the 20th century in either Region 2 or Region 3 during July, in contrast to the observations. This is an indicator that large scale changes in atmospheric circulation, forced by SST and radiative forcing changes, were not important for the observed increases in precipitation. However, there is potentially a large amount of uncertainty associated with the GCMs used here. While the GCMs may be able to capture some documented 20th century precipitation anomalies known to be related to atmospheric circulation anomalies, such as the floods in the early 1990s or the Dust Bowl in the 1930s [*Dirmeyer and Kinter*, 2009; *Schubert et al.*, 2004] (not shown), there are many differences between the models and observations that cannot be explained. These numerous differences imply that the portrayal of 20th century precipitation by the GCMs may not be reliable. Thus, we cannot rule out with high confidence that atmospheric circulation changes forced by SSTs and radiative forcing contributed in part to the observed precipitation increases.

[32] The prescribed SSTs in the GCMs investigated above incorporate information about temporal changes in the El Niño-Southern Oscillation (ENSO), the Pacific Decadal Oscillation (PDO), and the Atlantic Multidecadal Oscillation (AMO). However, uncertainty in the atmospheric response to the oceanic forcing in GCMs demands that the effects of such oceanic modes on Great Plains climate be investigated further. It is possible that a sudden change in the phase of any of the above oscillations could have been responsible for at least part of the observed sudden increase in precipitation seen in July, particularly in Region 3. Thus, we took a closer look at the observed phases of ENSO, PDO and AMO over the 20th century and their possible effects on Great Plains climate. *Hu and Huang* [2009] show that the phases of ENSO and PDO are associated with anomalies in Great Plains precipitation. In particular, they show that when both are in a positive phase, the region is wetter and when both are negative, the region is drier. Observations show that during the late 1940s, both ENSO and PDO switched to a negative phase (ENSO 20th Century Time Series (http://jisao.washington.edu/data/globalsstenso); PDO 20th Century Time Series (http://jisao.washington.edu/pdo/)). This would have favored a shift toward drier conditions in the Great Plains in the late 1940s [*Hu and Huang*, 2009], which is inconsistent with the precipitation observations. This provides evidence in addition to the GCMs that ENSO and PDO did not play a role in the observed July precipitation increases. As for the AMO, little documentation on its effects on Great Plains precipitation has been found in the literature, but there is no observed sudden shift in its phase at the time of rapid precipitation change in Region 2 and Region 3 during July in the 1940s (AMO 20th Century Time Series (http://www.esrl.noaa.gov/psd/data/timeseries/AMO/)). Thus, it also unlikely that the AMO was associated with the observed precipitation changes.

[33] Finally, initial inspection of the pattern of precipitation increase observed between the first and second halves of the 20th century in July, particularly in Region 3 (Figure 4), may suggest that irrigation along the Mississippi River could have played a role in the precipitation increase. However, a closer inspection makes it seem very unlikely that Mississippi irrigation had anything to do with the observed precipitation changes for several reasons. First of all, the Mississippi irrigation area (along the borders of Arkansas, Tennessee, and Mississippi) is well to the south of the observed precipitation increases [*Ozdogan et al.*, 2010], placing it in an area where the lower level winds would transport moisture to the east, rather than to the north (Figure 4). Second, the areal coverage and water use for Mississippi irrigation are both smaller than for Ogallala Aquifer irrigation [*Ozdogan et al.*, 2010], suggesting that Mississippi irrigation effects on precipitation would be weaker. Finally, there is indication that the increase in Mississippi irrigation over the 20th century occurred later than it did over the Ogallala [*Callahan and Barber*, 1985], making it unlikely that a precipitation response would be detected from the time periods put under analysis in this paper.

[34] In summary, the possibility of atmospheric circulation changes forced by SST and radiative forcing changes, and the irrigation near the Mississippi River were investigated for their possible role in the observed precipitation increases found during July. Despite the uncertainty involved in the analyses of the C20C GCMs, there is no clear evidence that any of these factors were particularly influential.

4. Summary and Conclusion

[35] Irrigation over the Ogallala Aquifer of the central United States increased dramatically over the 20th century and the possibility that this has enhanced regional precipitation has been investigated in this paper. A long-term record of station and gridded precipitation observations covering the entire 20th century shows that July precipitation increased 15–30% in a broad region downwind of the Ogallala Aquifer, stretching from eastern Kansas through Indiana. The month of observed precipitation increase falls within the seasonal peak of irrigation. Additionally, qualitative inspection of time series plots and the results of a non-parametric Pettitt test show that the July precipitation increased mainly around 1950, at a time when irrigation began ramping up significantly over the Ogallala. While the July precipitation increase was only statistically significant in a region far downwind of the Ogallala, the timing and spatial distribution of the broad precipitation increase is overall consistent with our hypothesis that Ogallala irrigation may have enhanced the regional precipitation.

[36] We also tested the hypothesis that added moisture over the Ogallala Aquifer actually increases the contribution of precipitation originating from ET over the aquifer. A DRM forced with observations of hydrologic variables shows that the contribution of ET from the Ogallala region (Region 1) to downwind July precipitation is 0.3–0.5 mm/day (2–6% of local total precipitation) greater when ET is higher relative to when it is lower. This suggests that increased ET over the Ogallala is partly manifested in higher precipitation downwind and that the increased ET associated with irrigation could have had the same effects. However, the results of the vapor tracking analysis show that the increase in precipitation originating from Region 1, when Region 1 ET is higher, is most intense immediately downwind of the Ogallala (Region 2), inconsis-

tent with the increase in observed precipitation being greatest far downwind (Region 3). This implies that not all of the observed precipitation increases in July, especially in Region 3, could have been associated with irrigation. Still, the fact that enhanced Region 1 ET contributes to greater precipitation downwind at all suggests that at least part of the observed July precipitation increases in Region 2 and Region 3 may have been associated with increased Ogallala irrigation.

[37] It is clear from the analyses in this paper that the observed precipitation increases downwind of the Ogallala in July are qualitatively consistent with the history of irrigation and mechanisms by which irrigation can enhance downwind precipitation. However, this does not prove that the irrigation is responsible for the observed precipitation increases, nor does it indicate how much of a contribution irrigation made to them. While the GCMs investigated here show neither statistically significant or robust precipitation increases at the same time as the observations, the uncertainty in their 20th century simulations does not entirely rule out that SSTs or atmospheric composition were partly associated with the observed precipitation increases. Furthermore, that the observed precipitation increases happened by chance due to the natural variability of Great Plains precipitation also cannot be ruled out. This is supported by the lack of significant precipitation increase in Region 2 during July and lack of August precipitation enhancement, resulting in no field significance of the collective precipitation increases. In summary, a controlled analysis of climate model simulations that includes the land surface changes associated with Ogallala irrigation is required to shed more light on this topic.

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