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NOTES AND CORRESPONDENCE

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ABSTRACT

The potential impact of the increase in irrigated areas in North America during the past 100 years on summer rainfall associated with medium- to large-scale precipitation systems is evaluated conceptually and by several illustrative numerical model simulations. The model results for the simulated cases suggest a tendency toward some increase in the continental-average rainfall for the present irrigation conditions compared with those of past irrigation. The maximum increase obtained for several studied cases of 6-day duration each was 1.7%. Rainfall increases typically occur in the location of existing rainfall areas, and the main effect of irrigation is to redistribute rainfall in those preexisting precipitation regions.

1. Introduction

Recent interest in global climate change has stimulated increased research activity in the estimation of changes in global rainfall. Several studies have noted a selective trend of increasing global rainfall (e.g., the survey by Foland et al. 1991). Specifically, these studies suggested that during the last few decades precipitation has tended to increase slightly in midlatitudes of the Northern and Southern Hemispheres, but in the Northern Hemisphere subtropics there has been some decrease. Various reasons have been suggested to account for these trends. Continental-scale temporal changes in landuse have been increasingly considered as factors affecting rainfall. Copeland et al. (1996) simulated an approximately 5% average increase in the July rainfall for the continental United States due to *various* landuse changes since the initiation of the European settlement in North America. Analysis of trends in observed summertime rainfall over the *present century* for the United States (Plantico et al. 1990) indicated a continental overall averaged increase of less than 1%. One of the most identifiable and quantifiable potential causes for these trends, within the context of landscape effect on evapotranspiration, is related to the development of irrigated agriculture in the past approximately 100 years. Increases in irrigated area create a net increase in the continental evapotranspiration and the atmospheric boundary layer moist static energy and thus should be thermodynamically considered as a factor affecting rainfall (e.g., Brubaker et al. 1993; Eltahir and Bras 1996).

Irrigated acreage in North America (as well as worldwide) has increased steadily and substantially during the 100-yr period ending in the mid-1980s. Growth in population and changes in agricultural practices contributed to this trend. Large increases in irrigation at the beginning of the century followed quickly behind the availability of electric power. The trend toward increased irrigated areas in the United States is depicted in Fig. 1, where the irrigated area expanded from approximately 0.015×10^6 km^2 in 1888 to approximately 0.2×10^6 km^2 in 1984. Similar trends also occurred in Mexico, where the irrigated area in 1984 was approximately 0.05×10^6 km^2. In Canada the present irrigated area (approximately 3000 km^2) is negligible by comparison.

In the present note, a preliminary evaluation is made of the potential change in North American rainfall attributable to the increase in irrigated area from medium- to large-scale rainfall systems. Its main objective is to evaluate the potential impact of increased irrigation acreage on North American summer rainfall under several climatic situations. Even if the absolute impact of irrigation on the continental rainfall is small, quantification of its role is needed to separate its influence from other possible anthropogenic influences on natural climate trends.

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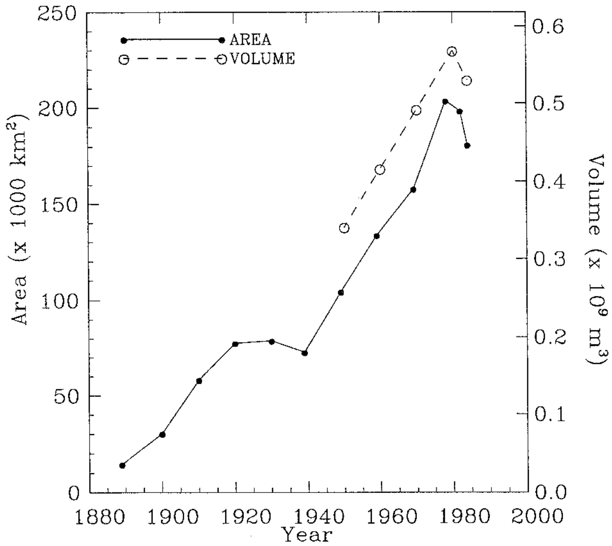

FIG. 1. Temporal changes in an irrigated area (1889–1984) and the annually averaged daily amount of water used for irrigation (1950–85) in the United States. [Reproduced from *The Water Encyclopedia* (1990) and Pastel (1993).]

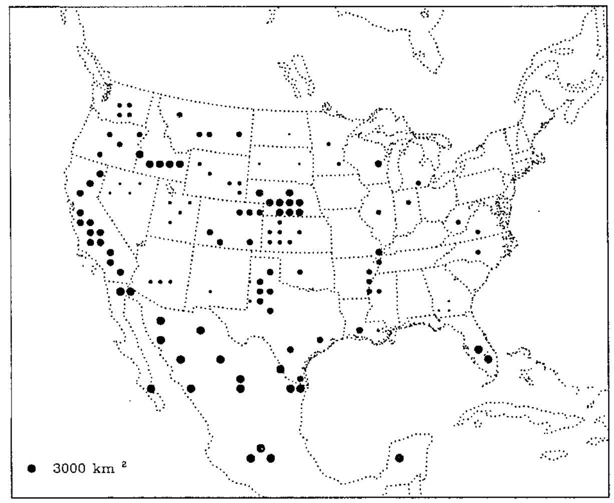

FIG. 2. Irrigated areas location and size (as scaled by the dark circles area) in North America and Mexico for 1984, with the largest circle representing 3000 km^2 (based on Moore et al. 1987; Segal and Arritt 1992; Pastel 1993).

A general description of the irrigated areas in North America and conceptual evaluations are presented in section 2, and illustrative numerical model simulations projecting the potential irrigation effect on continental rainfall are given in section 3.

2. Conceptual evaluations

The irrigated areas considered in the present study are depicted as dark circles in Fig. 2. It is based on the map of irrigated lands on farms issued by the United States Department of Commerce, Bureau of the Census for 1982 (see, e.g., Segal and Arritt 1992). The sizes of the circles are proportional to the irrigated acreage at those locations (the largest circle represents 3000 km^2).

Thermodynamically, summer rainfall potential tends to increase with an increase in the convective boundary layer (CBL) moist static energy. Betts et al. (1994) provided an excellent physical explanation regarding the thermodynamic impact of a change in the surface Bowen ratio on potential convective rainfall, which is used in the following conceptual evaluation. The increase in the irrigated areas resulted in a repartition of sensible and latent heat fluxes at these locations, whereas their sum approximately is unaffected. Therefore, to a first approximation, the change of dryland to an irrigated area is expected to yield a secondary effect, if any, on surface flux of moist static energy into the atmosphere (assuming an unchanged or a mild decrease in surface albedo and considering the reduction in soil thermal storage under irrigated canopies, it is suggested that the change to irrigated area would result in some increase in the surface moist static energy flux). However, the decrease in sensible heat flux associated with irrigation should suppress the development of the daytime CBL depth that *reduces* dry air entrainment at the top of the CBL. The entrainment at the CBL top *typically* reduces the CBL moist static enthalpy. Thus, overall evapotranspiration increases from irrigation enhance somewhat the characteristic moist static energy within the CBL and consequently is thermodynamically conducive to an increase in rainfall. Numerical model simulations at the global scale (e.g., Mintz 1984), the synoptic scale (e.g., Betts et al. 1994; Pan et al. 1995), and down to the local scale (e.g., Segal et al. 1995) indicated that increased surface wetness would support enhanced rainfall.

Variation in surface wetness through irrigation may also affect the atmospheric dynamics and consequently rainfall. Formation of local breeze circulation, though probably weak (Segal and Arritt 1992), associated with the irrigated area would tend to support moist convection. On the other hand, the impact of irrigation on other dynamical processes, such as the High Plains nocturnal low-level jet, might yield some decrease in the rainfall (e.g., Giorgi et al. 1996; Paegle et al. 1996).

Observational studies have not conclusively demonstrated the impact of irrigated areas on *local* deep convective systems and associated summer rainfall. Some observational studies implied an increase in *local* rainfall amount or number of rain episodes induced by the irrigated areas, whereas other studies have found no evidence for such effects (see survey in Segal et al. 1988). However, more refined recent studies suggest a positive impact (Eltahir and Bras 1996). The first author of the present note subjectively examined GOES visible imagery for the summers of 1988 and 1989 over large irrigated areas of the United States. This satellite imagery (in resolution of 1 km × 1 km) has not indicated a climatological pattern of *systematic development of*

TABLE 1. Continentally averaged accumulated rainfall P and evapotranspiration E for the nonirrigated cases for the six simulated cases and for the combined period of all simulations. Also provided are relative changes $\Delta P/P$, $\Delta E/E$, and $\Delta P/\Delta E$, where (Δ) indicates the difference between the irrigated (present) case and nonirrigated case.

Simulated case	P (mm)	E (mm)	$\Delta P/P$ (%)	$\Delta E/E$ (%)	$\Delta P/\Delta E$ (%)
1–7 July 1984	11.28	15.10	−0.16	1.47	−0.81
8–14 July 1984	10.66	15.67	1.72	2.03	0.58
16–22 July 1984	12.72	16.78	0.66	1.85	0.27
12–18 June 1988	6.79	16.90	1.14	1.90	0.24
17–23 July 1988	14.49	16.02	−0.32	1.85	−0.16
8–14 July 1993	16.24	18.76	1.23	0.98	1.13
All simulations	72.18	99.23	0.68	1.66	0.30

local deep convective systems in areas adjacent to the irrigated areas (Segal and Arritt 1992).

Some large irrigated areas are located in dry regions in the western half of the United States and typically receive only small amounts of rainfall, if any, during the summer. The remaining irrigated areas are located in regions not considered dry but having insufficient summer rainfall at the time it is needed for particular crops grown in the area. Thus, in the first type of irrigated areas, the enhanced evapotranspiration may serve as a moisture and moist static energy source for rainfall systems at considerable distances downwind. In the second type, the evapotranspiration may positively affect the thermodynamics of rainfall systems passing over the irrigated area, or they may play a role similar to that stated for the first type of irrigated areas. A numerical model can quantify both nearby and distant changes in precipitation caused by changes in surface evapotranspiration. Given the characteristics described above, it would be appropriate in most situations to employ a regional-scale model capable of resolving afternoon convection as well as meso-α systems (i.e., of horizontal scale 200–2000 km) to provide a scaling evaluation of irrigation impact on rainfall. However, possible occasional rainfall forced by meso-β systems (i.e., of typical horizontal scale less than or equal to 200 km) may not be resolved.

3. Numerical model simulations

a. Mesoscale model and simulation design

The fifth generation PSU/NCAR mesoscale model (MM5) was used in the present study (Grell et al. 1993). The modified Kuo cumulus parameterization scheme (Kuo 1974; Anthes 1977) was used in the present study. This scheme was found to be most sensitive to changes in the surface Bowen ratio (Pan et al. 1996) and is therefore likely to provide an upper bound to the investigated impact on rainfall. The MM5 aerodynamic formulation for evapotranspiration was used. This simple formulation is appropriate given the level of uncertainties in determination of the domain soil wetness, the horizontal grid resolution used in the study, and the constraint imposed on evapotranspiration from irrigated areas described later. The standard MM5 summer land-use distribution for North America was adopted. Validation of the model used here against observed rainfall characteristics showed reasonable results (see, e.g., Pan et al. 1996).

The simulation domain consists of a horizontal grid of 61 × 51 points with a resolution of 90 km (see Fig. 2) and 23 layers in the vertical with the lowest level about 5 hPa (approximately 40 m) above ground. With this resolution, the model can resolve meso-α scale systems with a horizontal scale of at least 360 km, but would not resolve meso-β meteorological systems (less than or equal to 200 km). Six illustrative cases of summer rainfall situations in North America (as listed in Table 1) were evaluated representing 1) a normal rainfall year (1984), three cases; 2) a flood year (1993), one case; and 3) a drought year (1988), two cases. In each case, the simulations commenced at 1200 UTC and were of 6-day duration (continuous integrations with observationally updated lateral boundary conditions). Two surface conditions were simulated for each case: a nonirrigated simulation in which evapotranspiration due to irrigation was excluded (i.e., corresponding to the minor irrigation extent approximately 100 years ago) and an irrigated simulation (i.e., corresponding to the present-day irrigation situation). See Fig. 2 for the location and extent of the irrigated areas. It is worth noting, however, that the main objective of the model simulations is to evaluate the differences between two situations where their surface thermodynamic forcing differs only mildly for the overall domain. Thus, the general features of the predicted rainfall fields in both situations should be similar. As a result, possible biases in the model predicted rainfall should be offset when the field of the rainfall differences is considered.

Irrigated areas in each state were mapped onto the numerical model grid, but since no irrigation location is large enough to correspond to an entire model grid box (8100 km^2), appropriate fractional irrigation areas were assigned to each model grid box. Man-made water reservoirs supporting irrigation compared to the irrigated areas are negligible sources of atmospheric moisture through evaporation. It is assumed that 1) all the water supplied for irrigation is used in the evapotranspiration process and 2) the peak amount of available water for summer irrigation consumption is used. We

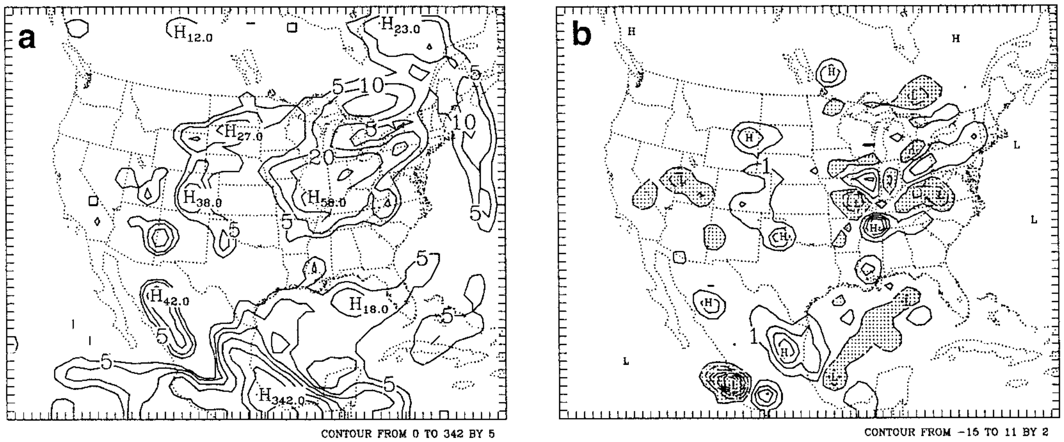

FIG. 3. (a) Composite of rainfall for the period 8–14 July 1984 for nonirrigated simulations. The contour levels increase by a factor of 2 (5, 10, 20, 40, 80, 160, 320 mm). (b) Composite of the difference in rainfall between irrigated and nonirrigated simulations for the period 8–14 July 1984. Contour interval is 2 mm. (Shading indicates differences less than −1 mm.) Here, ''H'' and ''L'' indicate local maximum and minimum values, respectively.

prescribed evapotranspiration rate E_i over the irrigated areas during the period from 0600 to 1800 LST, which translates into daily total evapotranspiration of 6 mm. The irrigated area in the simulated domain is approximately 0.25×10^6 km^2, which based on observational estimations (e.g., van Dewier Leeden et al. 1990; Pastel 1993), consumes an *annually averaged daily* amount of water of approximately 0.75×10^9 m^3. The prescribed total daily evapotranspiration in the present study corresponds to the summer peak possible averaged daily consumption of water for irrigation, which was estimated to be double the annually averaged. The averaged temporal variation of evapotranspiration rate E_i due to the irrigated area contribution was prescribed as

$$E_i = 6a_f \frac{\pi}{\tau} \sin\left(\frac{t - \tau/4}{\tau/2}\pi\right)(\text{mm s}^{-1}),$$
$$21\,600 \text{ s} \le t \le 64\,800 \text{ s}, \qquad (1)$$

where a_f is the fractional coverage of irrigation in a grid box, $\tau = 86\,400$ s, and t is local time in seconds ($t = 0$ at midnight). During the remaining day periods $E_i = 0$. The values of a_f range from 0.1 to 0.4, depending on the extent of the irrigated areas within a given model grid box. The adopted approximation of E_i accounts for reported estimation of available water consumption for irrigation in North America and provides an appropriate real-world consideration of evapotranspiration from grid boxes only fractionally covered by irrigated areas. Thus, for the purpose of the present study, this approximation should be more realistic when compared with applying a vegetation module in the subgrid irrigated locations.

Finally, the objective of the present note is to provide a preliminary estimation of increased irrigated areas effect on rainfall associated with large-scale systems. It is assumed that the accumulated simulation period is reasonable to establish this objective. Regional numerical model simulations evaluating sensitivity of surface wetness change effect on summer rainfall (e.g., Betts et al. 1994; Copeland et al. 1996; and Paegle et al. 1996) adopted a similar integration period to the one accumulated in the present study.

b. *Illustrative simulated rainfall fields*

Illustrative rainfall fields resulting from simulations of irrigated and nonirrigated surfaces are presented for three separate time periods representing the normal, flood, and drought years. The main features of the simulated rainfall fields were found to be generally supported by available rainfall observations. General characteristics of these simulations results are summarized in Table 1.

1) 8–14 JULY 1984

During this period, weak cyclonic and anticyclonic systems moved over the continent at the surface and 500-hPa level. In the eastern United States, rainfall was associated with the passage of a cold front.

The 6-day composite of accumulated rainfall for the nonirrigated simulation is presented in Fig. 3a. High values (greater than 20 mm) were simulated over parts of New Mexico, Colorado, and the northeastern United States. A very large amount of rainfall was simulated in southeastern Mexico. The simulation with irrigation produced increases and decreases in rainfall compared to the results without irrigation. The difference in rainfall between simulations with and without irrigation is presented in Fig. 3b. Over the continental areas, rainfall increases tend to have larger magnitudes of change than areas of rainfall decrease. Rainfall over the irrigated areas of Colorado, the Texas Panhandle, and northwestern Mexico increased in the irrigated simulation;

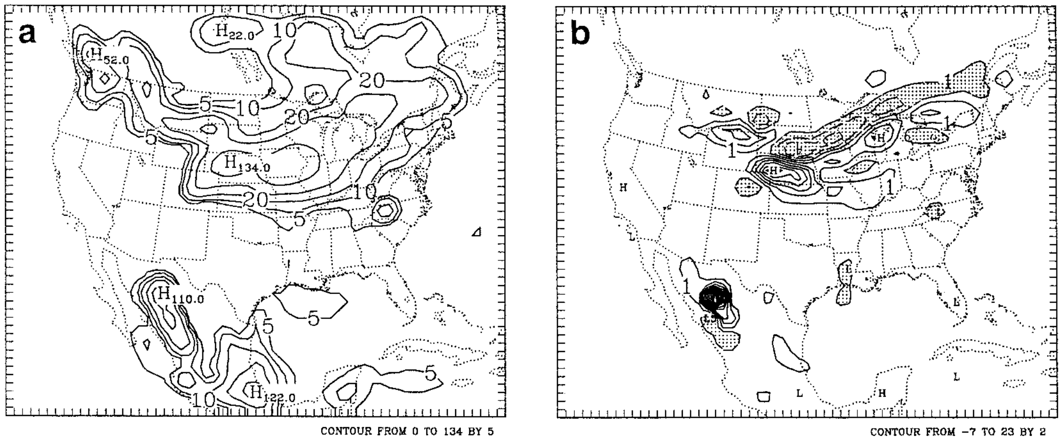

FIG. 4. As in Fig. 3 (a) and (b), except the period is 8–14 July 1993.

however, decreases were simulated over the irrigated areas in Idaho, as well as some locations in the eastern United States. It appears that the irrigated areas did not contribute to formation of new rainfall areas. However, displacements in the rainfall areas were simulated.

2) 8–14 JULY 1993

This 6-day period, during the Great Flood of 1993, had persistent features of the atmospheric circulation over North America contributing to excessive rainfall that has been well documented (e.g., Changnon 1996). In the beginning of the simulated period, a strong upper-level trough prevailed over the western United States, and a strong ridge stalled over the eastern states, whereas in the middle of the period, there was a trend toward a less-amplified pattern (i.e., more zonal flow). The initial pattern returned toward the end of the period. At the surface, high pressure dominated the northern High Plains and northern Rockies. During this period, a number of heavy rainfall events occurred that were associated with disturbances that developed and propagated toward Nebraska.

Figure 4a shows the nonirrigated simulated rainfall composite for this 6-day period. Affected areas are in the north-central and northern United States, as well as in northwestern Mexico. Figure 4b shows the difference between the irrigated and nonirrigated simulations. The areas affected by decreases and increases in rainfall are of about equal size, but the peak increases are noticeably higher than the peak decreases. The sharp contrast between increases and decreases in rainfall resulted mostly as the rainfall in the simulation with irrigation was intensified in the southern side and weakened in the northern side of the main rainfall area.

3) 12–18 JUNE 1988

This case occurred during a severe drought that was affecting much of the central United States. Development of a low pressure perturbation over the central United States resulted in some rainfall activity during this 6-day period.

Figure 5a shows the nonirrigated simulated rainfall composite for this 6-day period. Most rainfall areas are in latitudinal strips in the northern United States and southern Mexico. Figure 5b shows the difference between the irrigated and nonirrigated simulations. Areas of rainfall increase were about equal to areas of rainfall decrease. Most of the increases were in the north-central United States, and they were mostly over nonirrigated areas. This indicates the nonlocal effects of irrigation on rainfall associated with large-scale systems.

Note that the lateral boundary conditions used for each simulation were as observed for its respective time period. The observed vertical atmospheric profiles at the lateral boundaries (particularly outflow boundaries) might therefore be inconsistent with the profiles established in balance with the artificially changed surface conditions over land within the domain. These inconsistencies are mostly at the eastern and northern boundaries of the domain. However, these boundaries are located relatively far from the region of interest.

c. General characteristics of the simulated rainfall patterns

Table 1 summarizes the characteristics of the 6-day continentally grid-averaged accumulated rainfall and evapotranspiration in the six simulations (their magnitudes are the average per grid point over the continental portion of the domain). Also, the accumulations of rainfall and evapotranspiration for all simulations (6×6 days) are provided. Overall, the continentally grid-averaged accumulated rainfall P for nonirrigated conditions was lower than the corresponding evapotranspiration E. Additionally, the average differences in the continentally grid-averaged rainfall (ΔP) and evapotranspiration ΔE, between the irrigated and nonirrigated conditions were computed. In four simulations, the

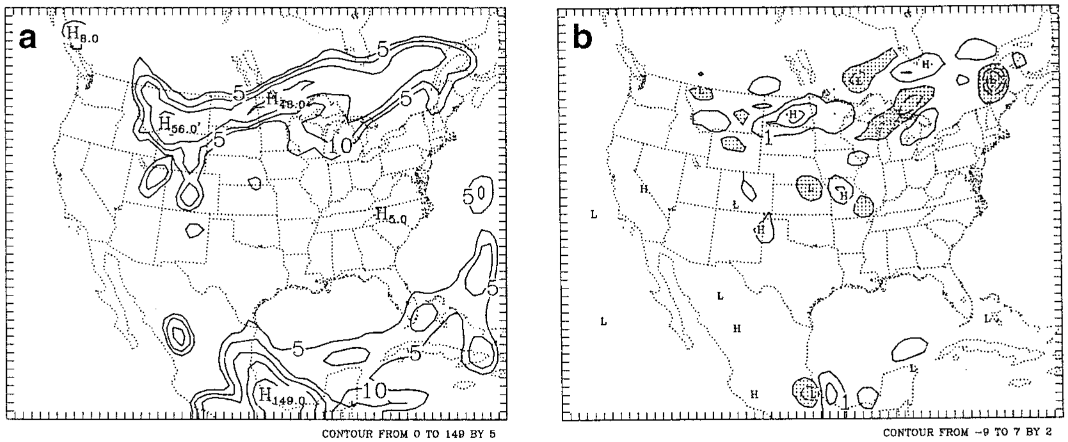

FIG. 5. As in Fig. 3 (a) and (b), except the period is 12–18 June 1988.

range of $\Delta P/P$ (i.e., the continentally normalized change of P for irrigated compared with nonirrigated conditions) was 0.66% to 1.72%, whereas for the remaining two simulations, decreases of 0.16% and 0.32% were simulated. For all simulations, the corresponding value of $\Delta P/P$ was 0.68%. Overall results suggest that the irrigation effect on the continental averaged rainfall tends to be slightly positive. This pattern may be compared with analysis of observed rainfall reported in Plantico et al. (1990), where an increase in summer continental average rainfall over the United States during the past approximately 100 years was determined to be approximately 1%. This observed change, however, includes impacts of all landuse changes, possible influences of rising CO_2, and (unknown) natural variations.

The simulated continental average $\Delta E/E$ values increased within a range of 0.98%–2.03%, while its value for all simulations was 1.66%. The increase reflects the additional contribution of evapotranspiration over the irrigated areas. However, it is worth noting that a decrease in the evapotranspiration was simulated in some areas due to increases in cloudiness and atmospheric moisture (not shown).

For additional insight, we define the efficiency for changes in evapotranspiration to cause changes in rainfall η, which implies the contribution of the irrigated areas to enhancement of precipitation, that is, effectively recycling:

$$\eta = \frac{\Delta P}{\Delta E}. \qquad (2)$$

For the summer season following Eltahir and Bras (1996), the domain-averaged value of η is likely to be less than or equal to 1. For four out of six simulated cases, the η values were in the range of 0.24 to 1.13, whereas for the other two cases, negative η values were obtained. When all the simulated periods are considered, $\eta = 0.3$.

4. Conclusions

Conceptual and numerical model evaluations were carried out to provide preliminary insight into the possible impact of the change in irrigation over North America on summer rainfall associated with medium- to large-scale atmospheric systems. Rainfall due to local convection was partially resolved in the model simulations, although details of local atmospheric dynamics for small-scale systems were not accounted for because of coarse model grid resolution. In some of the irrigated areas, summer rainfall is rare or infrequent, so changes in local atmospheric dynamics probably are not sufficient to trigger or contribute to summer rainfall. However, considering such local possible contribution, we suggest that changes in irrigation area (as accounted for in the present study) provide, within the context of the stated model constraints, an initial conservative lower limit for estimation of the related changes in rainfall at the summer peak irrigation periods.

In the present note, illustrative cases were presented to provide a preliminary model assessment of the range of possible impacts of change in irrigation on summer rainfall over the last approximately 100 years. The simulated effects of irrigation on rainfall in the illustrative cases appear to be mostly nonlocal since the modifications to rainfall did not coincide with irrigation locations. Most of the increase in rainfall under the present pattern of irrigation was simulated over the continent. It is evident that increased rainfall in the irrigated cases was largely simulated in areas of preexisting rainfall; that is, the impacts of irrigation on the resolvable rainfall systems were generally so weak that hardly any new rainfall areas were generated; rather, irrigation only altered existing rainfall fields. In some instances, such as when the atmosphere is convectively unstable, this effect might be significant due to displacement of heavy rainfall centers. Application of fine-grid meso-β model over the various irrigation areas is needed in order to estimate the potential contribution of small-scale systems to the rainfall. Multiyear long-term simulations are required for a comprehensive study in order to establish a refined modeling estimation of the impact.

Other changes in landuse during the past approximately 100 years have occurred in addition to the increase in nonirrigated crop area (e.g., deforestation, afforestation, wetland drainage, urbanization, vegetation changes from grasses to crops); however, not all of these changes have a monotonic temporal trend, and some may produce thermodynamically opposite effects on summer rainfall. Also, quantifying these changes for modeling purposes cannot be done as rigorously as that for irrigation. It is likely, however, that the overall change in landuse has a larger impact on rainfall compared with the change solely related to changes in irrigation.

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