Climate Response to Irrigation in the American West

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ABSTRACT

Significant changes in population and cultivation of farmland in Western U.S. over the past 200 years has required the use of extensive irrigation to sustain crop growth in the region. This irrigation has altered the land surface processes in the region and subsequently the local climates by increasing soil moisture levels higher than they naturally would be if no irrigation had taken place. Analysis of feedback processes show both positive and negative feedbacks are present and impact climate parameters such as surface temperature, precipitation, and albedo. Literature suggests that in the western plains the dominance of positive or negative feedback is determined by the intensity, spatial scale, and duration of irrigation, as well as synoptic scale patterns.

The intermediate model QTCM was used to simulate irrigation of Western U.S. growing season (May-Nov) over the period of 1990-1999. Monthly climatological sensitivity experiments were conducted over a range of irrigation forcings from realistic values to near saturation of the soil. The results show a slight climatic response to realistic forcing and a significant climatic response to saturated forcing. All experiments indicated a positive feedback and agree with previous studies of large scale increases in precipitation, decreases in surface temperature, and increases in albedo over irrigated regions. Additionally simulations suggest that the QTCM model has a threshold of sensitivity to the irrigation forcing of 1.0 mm/day. Any forcing greater than this does not show significantly further climatic impact in the model.

Future work for refining the accuracy of irrigation forcing would include using non-uniform distribution of irrigation in a higher resolution model, considerations of altitude, refining of seasonal dependence of crop growth, and a trend analysis. Globally research of regions such as China and India have not been well explored and experience even more irrigation than Western U.S. Irrigation raster maps could be incorporated into a GCM to simulate global irrigation and study climatic impacts of realistic forcings.

1. Introduction:

The American West has undergone significant changes over the last 200 years. A rough terrain of woodlands, plains, and wilderness has given way to an organized patchwork of agriculture and urban areas prompted by extensive increases in population and subsequent cultivation of the region. Climate dictates that the western U.S. region has relatively little available moisture during summer months in the form of precipitation. This fact prompts the farmers of the Great Plains and western plateau regions to use irrigation to water crops that would otherwise be impossible to grow in these areas.

The total amount of water used over irrigated regions is significant. The area is vast and encompasses 38.5 million acres, roughly 8% of the total land area of the region. Irrigation accounts for 9.39e13 liters per year which is 34% of the total groundwater budget for the Western U.S. 1998 estimates by the USDA (Figure 1) show that this is approximately 2.81 mm/day. According to data from Earth Observation Research Data Center 1990 study the distribution of irrigated cropland west of the Mississippi River is fairly evenly distributed within the Great Plains, and concentrated in the valleys of the Sacramento River in California, and Columbia and Snake Rivers in the western plateau region.

Irrigation of land in these areas creates some obvious changes to the land surface. The process literally pulls water from underground and spreads it over land. This increases the soil moisture and vegetation growth during the growing season giving the same affect as if it had rained a steady drizzle. The climatic implications of this additional forcing are not completely obvious, and the next section will show competing feedback processes that depend on multiple parameters of the situation.

2. Irrigation Processes

a. Feedbacks

This study focuses on the dynamic and thermodynamic consequences of increasing soil moisture in general. A surface roughness feedback study was omitted because the changes in roughness characteristics before and after irrigation took place would have been minimal. The roughness difference between grasslands and cropland would not have been enough to increase the turbulence within the boundary layer any significant amount in this region. Therefore two major competing feedback processes associated with irrigation in the region were compared.

The positive feedback process is as follows: (1) irrigation brings water to the surface, (2) leading to increased soil moisture. (3) As crops grow the evapotranspiration increases due to more available water, (4) relative humidity increases above irrigated region, (5) instabilities naturally formed contain more water vapor which leads to more convective cloud formation. (5) This increases the chance for more precipitation over the region, and (6) leads to an increase in soil moisture. This process indicates that the addition of irrigated water onto the land surface would increase the precipitation process and cloud cover.

The negative feedback process is as follows: (1) irrigation brings water to the surface, (2) leading to increased soil moisture. (3) As crops grow the evapotranspiration increases due to more available water, (4) which leads to latent heat absorption, (5) reduced temperature of the air close to the surface, and (6) the creation of a stable environment acting to suppress convective cloud formation. (7) This leads to clear skies and finally (8) reduction in soil moisture. This process indicates a reduced surface temperature and dry soil conditions associated with irrigation.

b. Literature Reviews: GCMs

The feedbacks described above show the hypotheses of physical processes that might influence the climate regime of the Western U.S. Comparison of studies show not only that these processes are evident, but also that these processes can be used to infer the climatological effects of increasing irrigation.

A numerical experiment conducted by *Yeh et al*. [1984] explored the persistence of soil moisture anomalies of large-scale irrigation in the Midwest plain states and the climatic impacts. To conduct this experiment Yeh et al. used a rather simple GCM developed by Wetherald and Manabe which incorporated a general circulation of the atmosphere, heat and water balance over continental regions, a simple mixed-layer ocean, and idealized flat geography. The experiment focused on 19 year zonally averaged climatologies in three regimes: 30-60N, 0-30N, and 15S-15N and analyzed the persistence of anomalies due to initial saturation of the soil. For the purpose of this present study the 30-60N regime was of great interest. The saturation of ~15cm on all continental surfaces was performed for one day on 1 July. Figure 2 shows the results of the 19 year run and the impact on three climate parameters of soil moisture, precipitation, and surface temperature. Soil moisture increased and persisted for several months at better than half of the initial value, precipitation increased dramatically and persisted for several months, and surface temperature decreased by more than 12 C, however did not persist for very long. The conclusions drawn by Yeh et al. show that not only do anomalies persist, but also are advected meridonally out of the zonal constraints. Enhancement can occur in areas of irrigation and adjacent regions, but persistence is strongest near regions of rain belts and weak near regions of general subsidence. This indicates that feedback responses are highly latitude dependent, and irrigation can actually reduce precipitation in areas of subsidence.

Similar results were found by other modeling studies. *Shukla and Mintz* [1982] tested two global scenarios of a very dry-soil case where there was no evapotranspiration and very wet-soil case where evapotranspiration was always equal to the potential evapotranspiration. For the wet-soil case there was a precipitation increase whereas the dry-soil case a precipitation decrease was shown. Also the surface temperature of the dry-soil case was much higher than that of the wet-soil case. *Rind* [1982] compared initially reduced soil moisture with control runs on June 1 across North America and found the anomalies to have significant temperature increases and precipitation decreases across the U.S.

c. Literature Review: Regional Climate Studies

Though the GCM studies above indicate the validity of the positive feedback processes regional climate studies on the other hand did not find the same conclusions when analyzing localized soil moisture feedbacks. *Georgakakos et al.* [1995] studied two 2000 sq km basins in Iowa and Oklahoma. Using daily precipitation and potential evapotranspiration they simulated river discharge over a 40 year period. They found no precipitation feedbacks associated with the soil moisture. *Giorgi et al.* [1996] argued the same. Local recycling effects do not impact climatic regimes. In fact, dry initial conditions provide increased sensible heat flux which leads to more cloud development and subsequent precipitation. Dry soil actually produces precipitation.

However an extensive observational study conducted by *Findell and Eltahir* [1997] showed that a large distribution of measurements of soil moisture and rainfall does indicate positive feedback. Findell and Eltahir analyzed direct observations of soil moisture-rainfall feedback using the Illinois Climate Network (ICN). The ICN consists of 19 sites well distributed in the state that collect biweekly soil moisture data and 129 daily precipitation stations. The study was conducted over a 14 year period to get a high-quality climatology of the region. Results show (Figure 3) a strong correlation between initial soil saturation and rainfall in summer months with a peak of r^2>0.4. While not the only physical process involved, the correlation suggests a significant positive feedback.

Additionally *Barnston and Schickendanz* [1984] studied the effects of large scale irrigation of the southern Great Plains on precipitation. They conducted EOF analysis on a 10-year period. Their results indicated a deficit of the maximum temperature of 1.7 to 2.1 C over the irrigated regions, but also through the EOF analysis determined the importance of synoptic features on the correlation of increased soil moisture and precipitation. A positive feedback requires the additional moisture from the irrigated regions to be allowed to ascend to the cloud base. This requires lifting mechanisms and precipitation increases only when synoptic conditions provide low-level convergence. The best conditions were found to be slow moving low pressure centers or stationary fronts.

3. Modeling Western U.S. Irrigation

These studies indicate that the intensity and direction of irrigation feedbacks are highly dependent on latitude, the initial conditions, extent of irrigation, special scales synoptic features, and seasonality. Smaller regions over shorter times tended to show no feedback or even negative feedbacks while larger areas with several years of data tended to indicate strong positive feedbacks. Synoptic features during summer months (JJA) will even out when climatology is conducted over several years, so the focus of this paper's experiments will be the large scale features. The following modeling experiments were conducted to show large scale effects of irrigation on regional climate zones similar to that of Yeh et al.

ca. Plan & Design

The model QTCM was chosen for this series of experiments. The QTCM was developed for analysis of tropical regions, but has proved to be sufficient for use in extra-tropical regions for our current purpose. It is a coupled land, ocean, vegetation, and atmospheric intermediate model with a rather coarse grid resolution of 5.625 X 3.75 degrees and a daily time resolution. Being an intermediate model the QTCM is not quite as sophisticated as a full scale GCM, and has several approximations built in to save computing time. These include winds that are divided into baroclinic and barotropic modes, long-wave and short-wave radiation schemes, and clouds categorized into deep convective, high cirrus, stratus, and cirrostratus among others. The treatment of soil parameterizations was especially important in the choosing this model. It is a single layer but with different depth for the energy and water balance. The prognostic equation for ground temperature is as follows:

$$C_s \frac{\partial T_s}{\partial t} = F_s^{rad} - E - H$$

The prognostic equation for the water budget is as follows:

$$\frac{\partial W}{\partial t} = P - E_I - R_s - E_T - R_g$$

Another motivation for choosing this model was it's simplicity. The parameterizations made computing time and power much less than running a full scale GCM. For example to run 10 years of data requires only ~1.5 hours. A full scale GCM may take more than 24 hours to run the same 10 years. Additionally it is a good first approximation to understand the general processes of this experiment.

The basic setup of the experiment is this: (1) select a region to force with irrigation, (2) select a time period to form a climatology for that region, (3) observe a control run with no forcing, (4) conduct a series of runs with different magnitudes of forcings and (5) compare the anomalies with the control run.

The region of interest was the western portion of the U.S. Therefore the boundaries of 25-50N and 95-130W were chosen covering a 7X9 grid area which is a total of 63 grid points. Because the grid resolution was coarse, there would not have been an advantage of weighing the irrigation forcing to grid points located near higher rates of actual irrigation within the boundaries. Therefore uniform distribution of forcing was implemented. Since realistically irrigation would only be used for the duration of the growing season irrigation forcing was turned on for the months of May to November and then turned off for the winter months.

Several runs were conducted over 11 years of 1989-1999 with the first year reserved as a spin up year. The atmosphere reacts rather quickly to the forcings, so the spin up was sufficient for this current study. The runs included a control run where no irrigation was added, and a series of incrementally increasing forcings of 0.5, 1.0, 2.0, 5.0, and 10.0 mm/day added to the land surface. Additionally a realistic forcing run based on the USDA 1998 number of 2.81 Km^2*mm/day was conducted also. This calculates to be about 0.25mm/day of water added to the surface of an irrigated areas.

The climatic response was evaluated using the parameters of surface temperature, precipitation, and leaf area index (LAI). The LAI is a measure of the greenness of the land surface and infers an albedo for that grid point in the following equation:

$$A = 0.38 - 0.3(1 - e^{kL})$$

b. Results

In order to make sure that the area within the designated boundaries was correctly assigned and that the model would be sensitive enough, a spatial distribution check was conducted. Figure 4 shows soil wetness for both the control run and the most extreme case of 10 mm/day. The additional surface forcing is evident in the S_10 run marked by a high saturation across the western U.S. This also indicates that the choice of forcings will impact climate parameters in the region.

Figures 5-7 show area averaged time series of surface temperature, precipitation, and LAI over the ten-year period for different values of forcing in the Great Plains. This was conducted to check the consistency of the data and ensure that the forcings did not induce numerically unstable results. The time series clearly show the forcing signatures on the climate parameters. Figure 6 shows a significant increase in precipitation over the region, especially in the summer months. Figure 7 does appear to have a slight nonlinearity in the first 5 years. This was due to the slower reaction of the vegetation to the irrigation forcing and was expected. To correct this, a longer spin up time needed to be implemented. However the data clearly shows the significant increase in LAI as irrigation in the region is increased.

Because the summer season (JJA) showed the most visible changes in the climate fields with the addition of the irrigation, the next step was to analyze the JJA anomalies of the sensitivity runs from the control run. For this three only three forcings were represented: S.25-Control, S1-Control, and S10-Control. Figures 8-10 show the signal of the realistic S.25-Control is very weak in all three parameters, but S1-Control anomalies are visible. Surface temperatures are reduced by as much as -2 C in some places indicating a higher percentage of clouds in the region. Precipitation is increased by 1 to 3 mm/day in the region and also there is a fairly strong precipitation signal on the east coast. This precipitation tongue is most likely associated with the prevailing winds over the continent and the synoptic wave patterns that develop. In reality it is unclear if this could be physical because as shown by *Nigam* [2006] almost all of the atmospheric moisture in the Midwest does not advect out of the region during summer months, but is recycled via local precipitation. LAI anomalies show significant increases in foliage at the S1 forcing. For all parameters the S10 anomalies display a maximum change for those parameters.

Sensitivity of the model to forcing was shown to be determined by the parameter being observed where each parameter had a different response. Figures 11-13 displays the seasonal response of surface temperature, precipitation, and LAI versus the forcing values. Though the responses were different, all three parameters had the biggest response in the forcing values below 1.0 mm/day. Figures 14-16 show the percent changes during the summer months were largest for values below the threshold of 1.0 mm/day. This is because above this forcing value the model begins to saturate. There is a limit to how much precipitation will occur and likewise cloud cover which will control the surface temperature and LAI values. Above this threshold runoff processes will transport the excess surface water out of the region when the ground is close to saturation.

c. Analysis

This simple experiment demonstrated that large scale irrigation would have impacts on the local climate. Model results show an increase in precipitation, a decrease in surface temperature, and a decrease in albedo inferred by increase in LAI. Depending on the amount of irrigation forcing the degree of response could be trace or substantial. Also it is possible that large scale irrigation is responsible for impacts on climate in adjacent regions because of advection.

The data indicated a realistic forcing value of 0.25 mm/day for the Western U.S. but this did not appear to significantly impact the climate in the region. The forcing of 1.0 mm/day did however show a strong signal. *Zeng et al.* [2000] indicated that the QTCM has an overly fast runoff process that tends to dry up the soil sooner than it should. Figure 17 shows the model precipitation-runoff time series for the Mississippi River compared with the observed precipitation-runoff. In general the model data underestimates this value which would lead higher soil moisture being needed in the model to compensate for the fast runoff. Therefore the realistic value of 0.25 mm/day of irrigation forcing is too low for this model. A value closer to 1.0 mm/day would be more appropriate.

4. Future Work

For future study there are several improvements that could be made to this model study. Choose a more sophisticated model with a smaller grid size and compare results with current study. Refine the realistic irrigation data by weighing data distribution to reflect actual density of irrigation networks, altitude considerations, and refine seasonal dependence of crop growth. Additionally a trend analysis would be interesting to study the impacts of increasing irrigation over the region.

The U.S. is not the only country engaging in large scale irrigation. China and India are even more heavily irrigated then Western U.S. The incorporation of digital mapping of irrigated regions globally could be used to study irrigational effects on global circulation and climate regimes. The Food and Agriculture Organization has developed a high resolution (5 min) raster map of irrigated land areas. Information has been compiled from government reports where possible and statistical interpolation where not possible. Figure 18 shows the raster map with concentration of irrigated areas. Digital maps can be integrated into GCM modeling experiments. This will supply more realistic global forcing, and provide insight into how far reaching irrigational impacts are to regional and global climates.

5. Conclusion

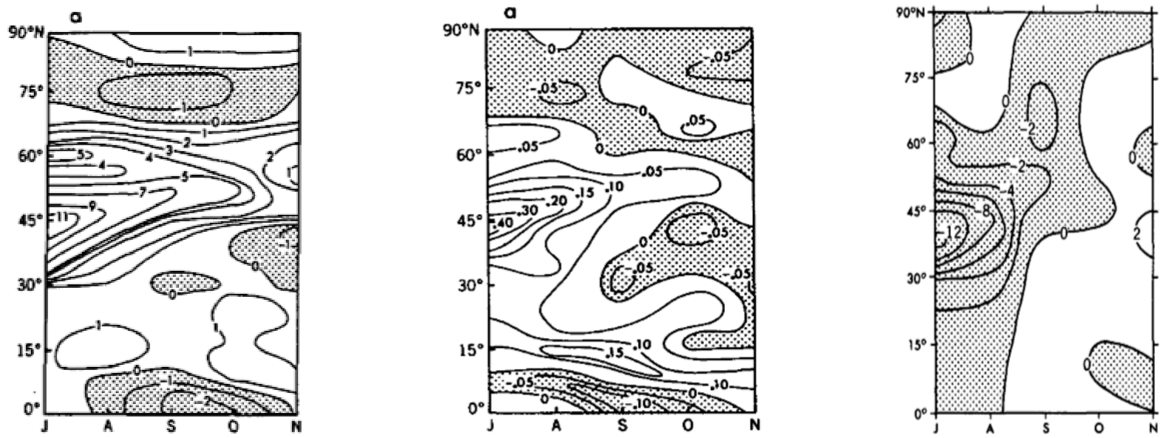
Large scale irrigation forcing is responsible for a positive feedback on a regional level causing increased precipitation and decreased temperature. Literature suggests dependence on spatial scales, distribution and intensity of irrigation, climatic regimes, and synoptic conditions, but over a large spatial scale and sufficiently long timescales, the dependency is merely on the amount of irrigation forcing that is applied.

The realistic forcing value of 0.25 mm/day is nearly undetectable using QTCM, and must be increased within this model to compensate for fast runoff processes.

Total irrigated acres and water distribution by state for 1998 FRIS irrigated farms.

State	Acres	Km^2	Acre feet (1000)/season	Km^2*mm /day
Arizona	873,589	3,535	4,117.7	0.15
California	8,139,834	32,941	25,154.9	0.93
Colorado	2,942,230	11,907	5,052.9	0.19
Idaho	3,188,406	12,903	6,030.7	0.22
Kansas	2,650,486	10,726	3,589.6	0.13
Montana	1,740,873	7,045	2,887.1	0.11
Nebraska	5,692,215	23,036	4,975.3	0.18
Nevada	694,930	2,812	1,939.4	0.07
New Mexico	720,319	2,915	1,729.9	0.06
North Dakota	164,741	667	140.6	0.01
Oklahoma	451,788	1,828	677.2	0.02
Oregon	1,534,961	6,212	3,255.7	0.12
South Dakota	297,205	1,203	311.8	0.01
Texas	5,237,584	21,196	7,474.5	0.28
Utah	1,076,346	4,356	2,701.4	0.10
Washington	1,554,813	6,292	3,364.8	0.12
Wyoming	1,533,468	6,206	2,780.1	0.10
Total: Western States	**38,493,788**	**155,779**	**76,183.6**	**2.81**

Figure 1. USDA 1998 Estimates Farm and Ranch Irrigation Survey (FRIS)



Soil Moisture (cm) **Precipitation (cm/day)** **Temperature (C)**

Figure 2. Latitude-time distribution of the zonal mean difference (15cm-Control) of soil moisture, precipitation, and surface temperature. *Yeh et al.* [1984]

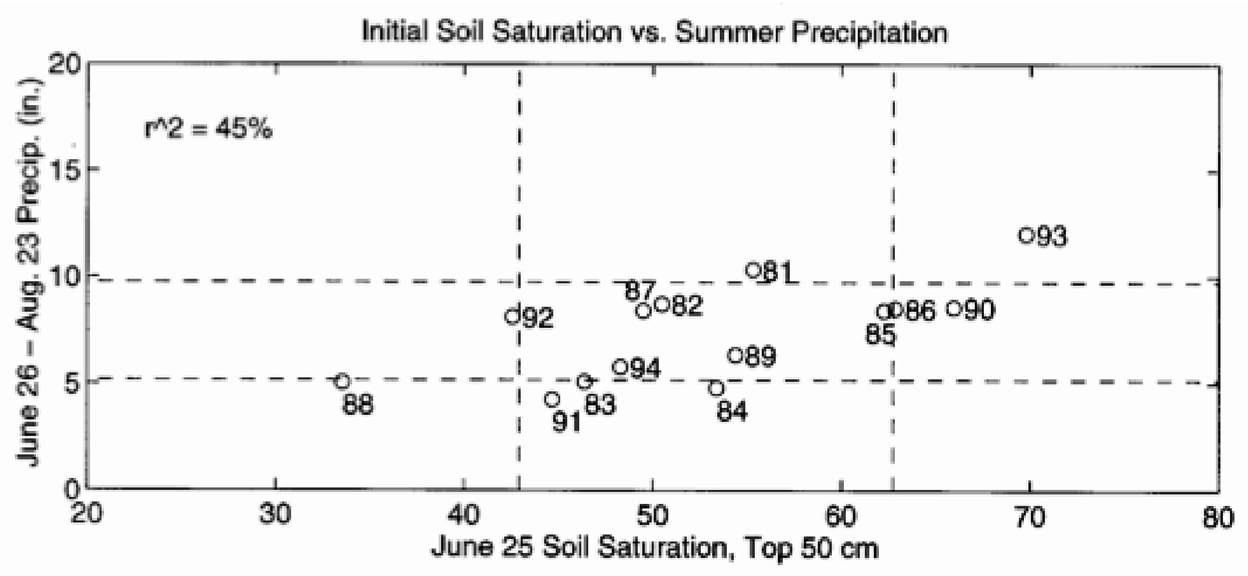


Figure 3. Correlation of soil saturation and precipitation for JJA. *Findell and Eltahir* [1997]

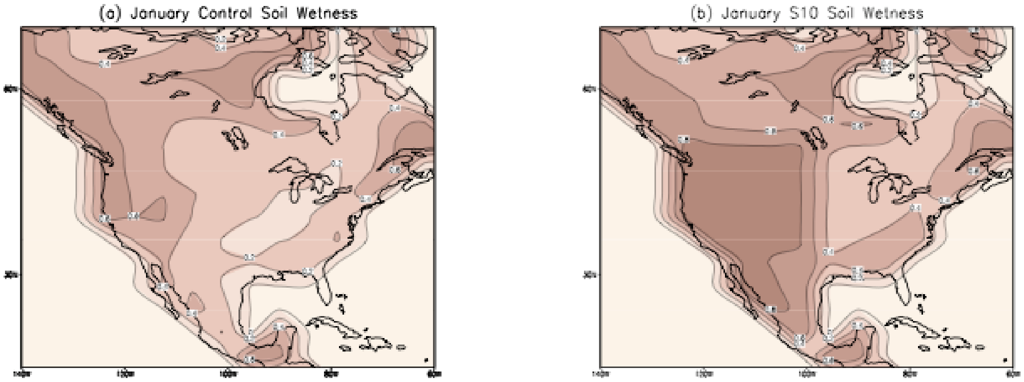


Figure 4. Spatial and intensity test: Soil wetness increased dramatically from the control run (left) and the S10 run (right) where 10 mm/day of water was added to the entire western region.

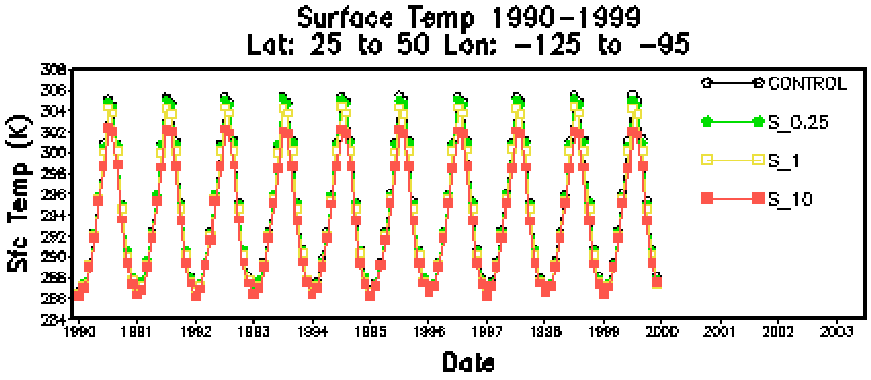
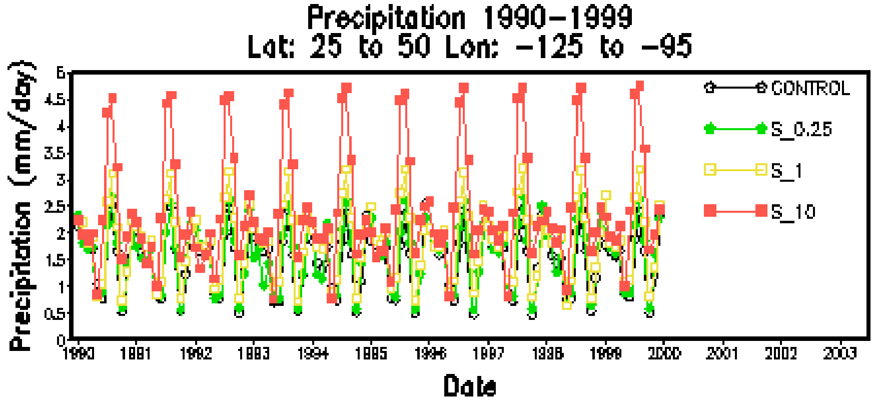
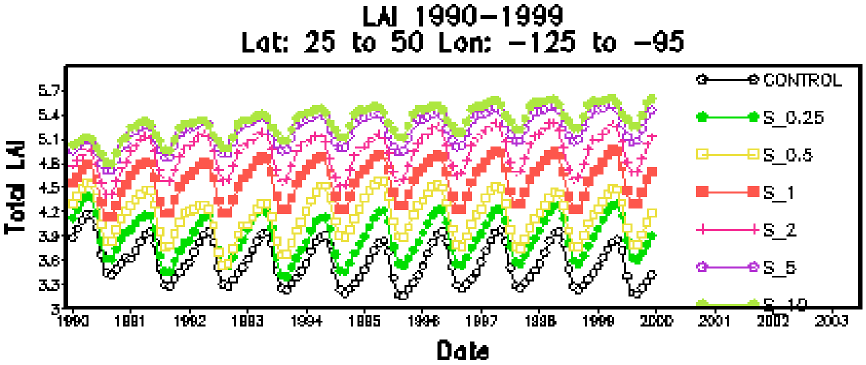


Figure 5. Time series of sfc temp for forcings.



GrADS: COLA/IGES

Figure 6. Time series of prec for forcings.



GrADS: COLA/IGES

Figure 7. Time series of LAI for forcings.

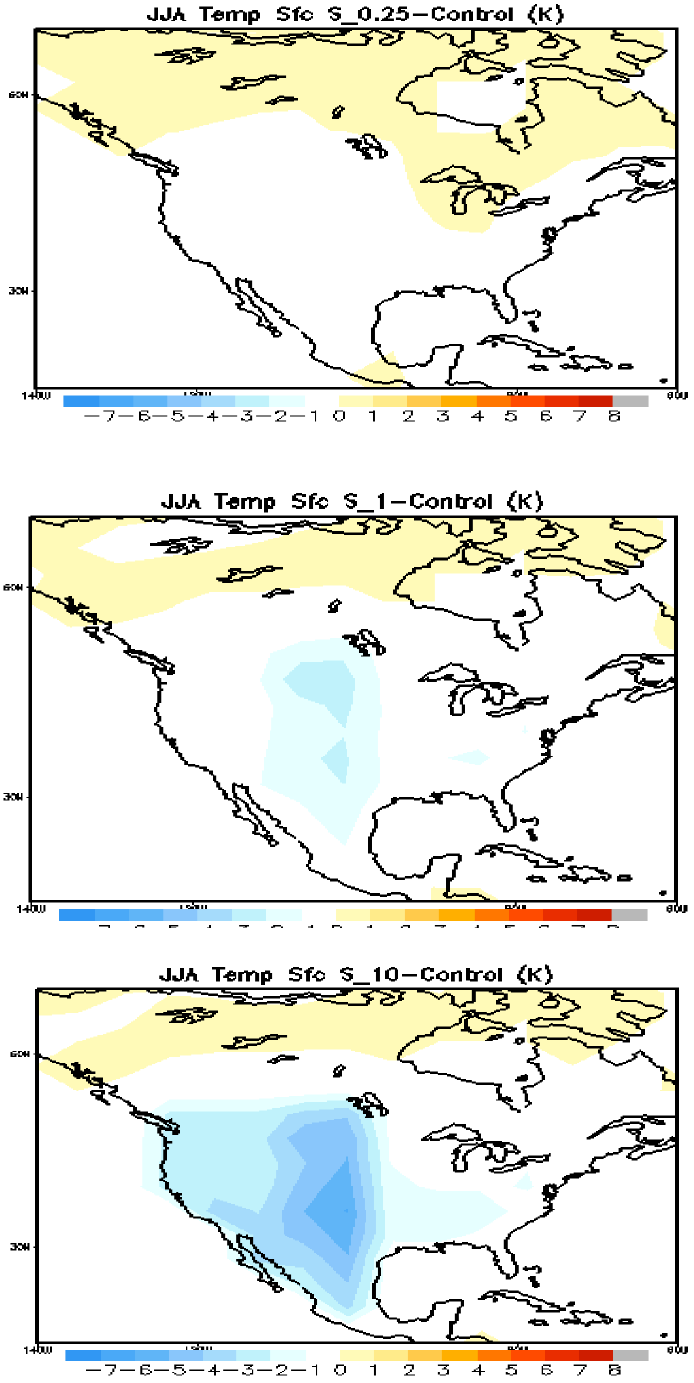


Figure 8. Sfc temp (K) anomalies for S.25, S1.0, and S10.

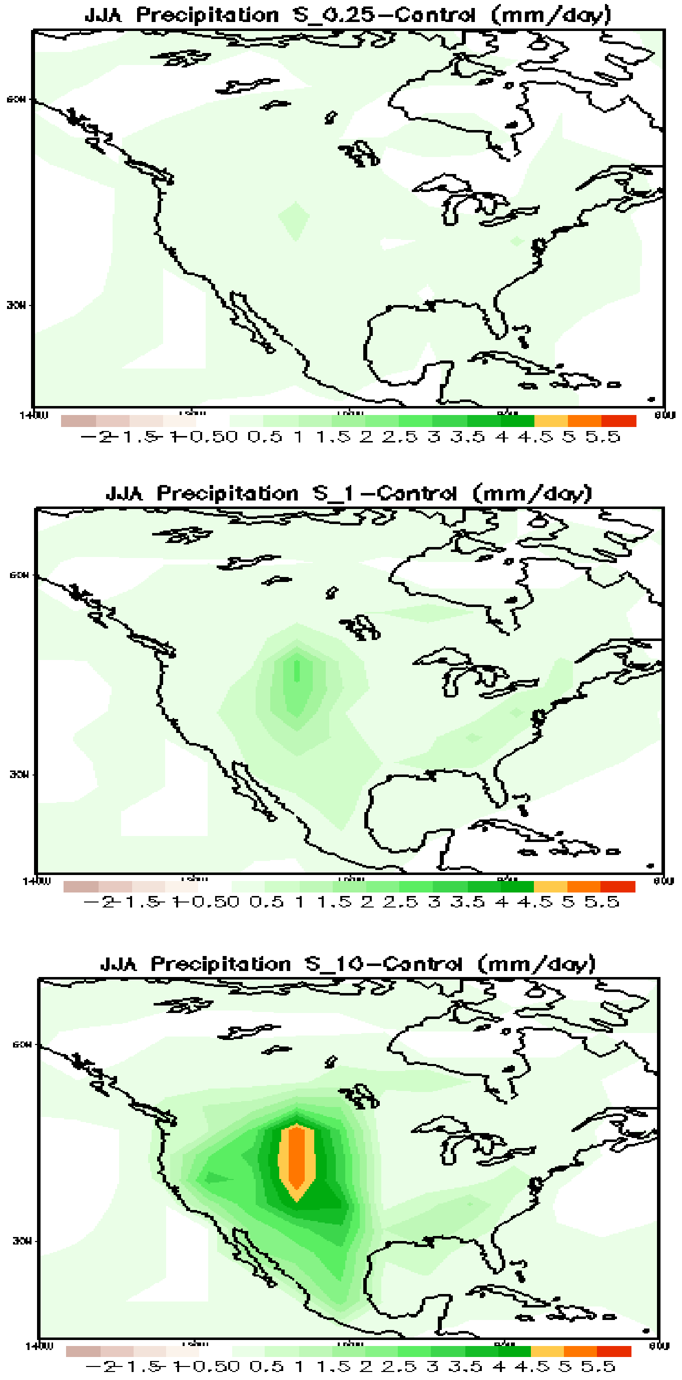


Figure 9. Precipitation (mm/day) anomalies for S.25, S1.0, and S10.

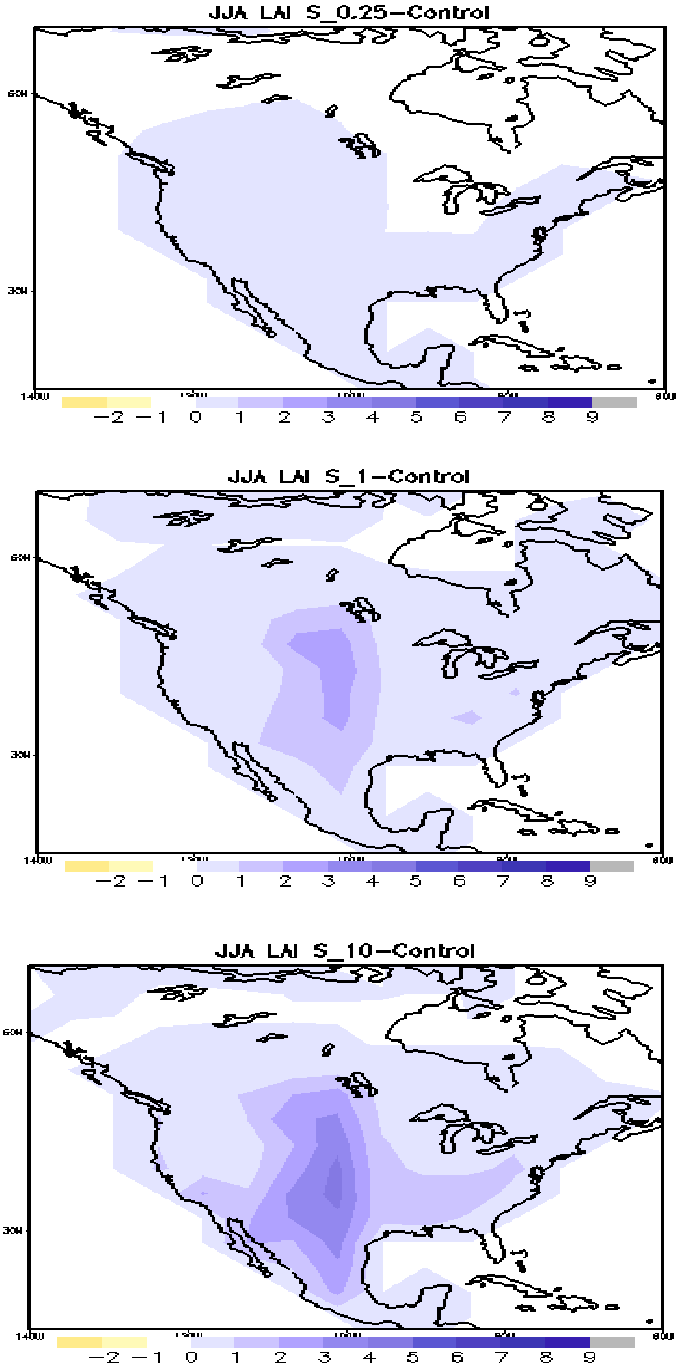


Figure 10. LAI anomalies for S.25, S1.0, and S10.

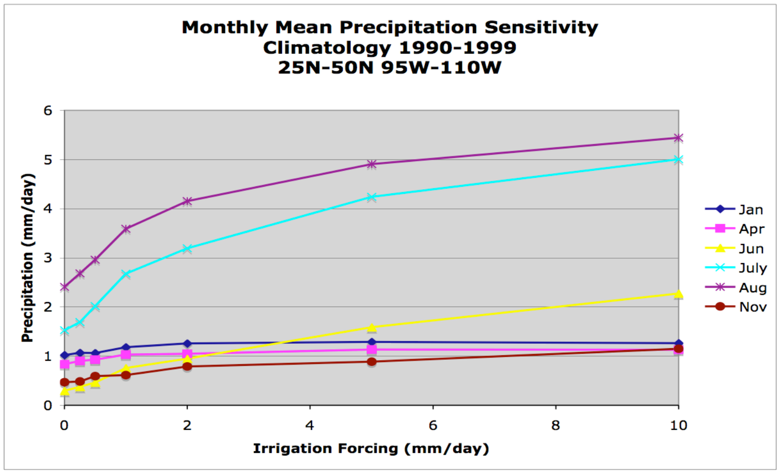


Figure 11. Monthly mean prec sensitivities to irrigation forcings.

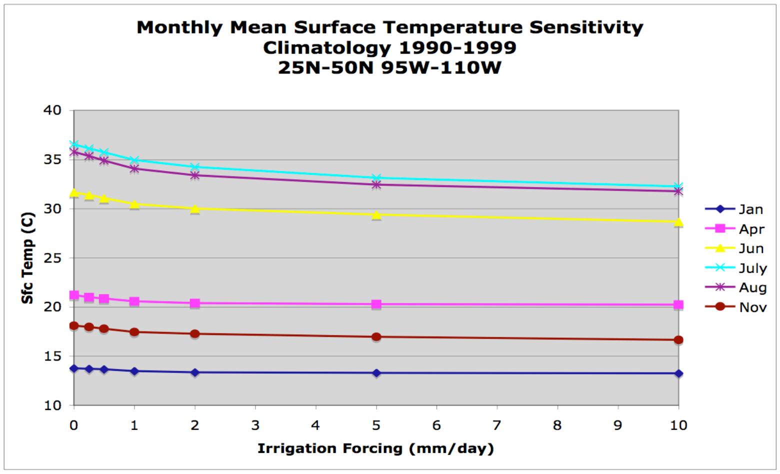


Figure 12. Monthly mean sfc temp sensitivities to irrigation forcings.

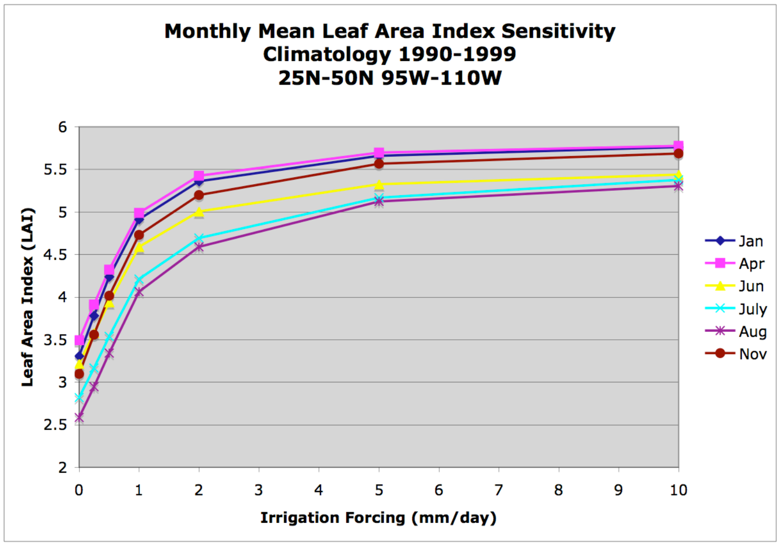


Figure 13. Monthly mean LAI sensitivities to irrigation forcings.

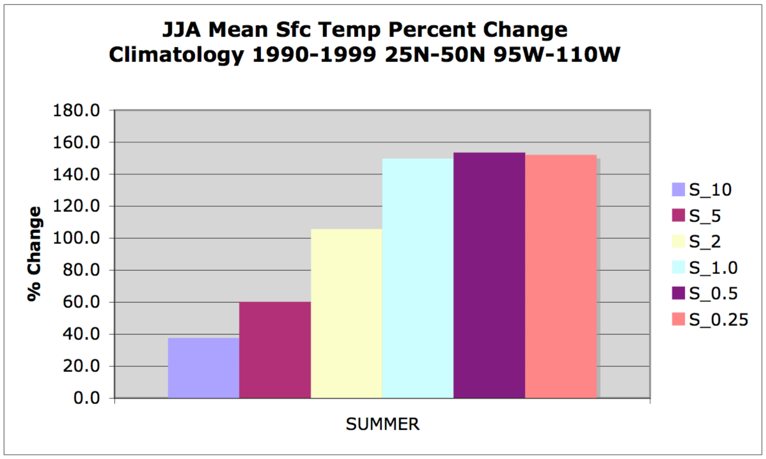


Figure 14. JJA % change of mean sfc temp by each forcing.

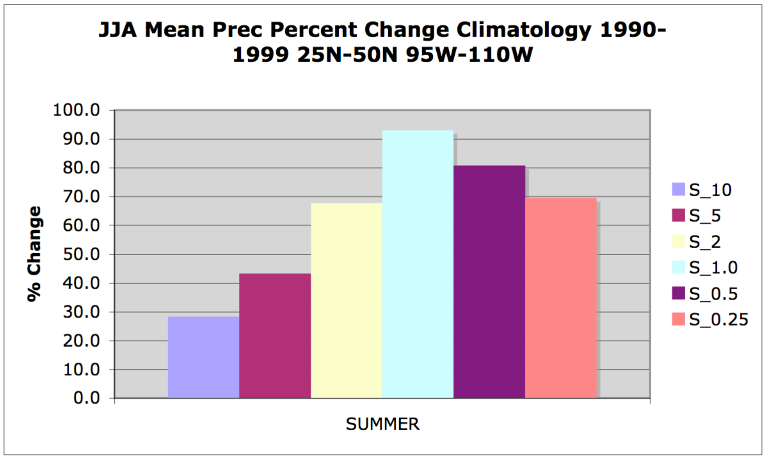


Figure 15. JJA % change of prec by each forcing.

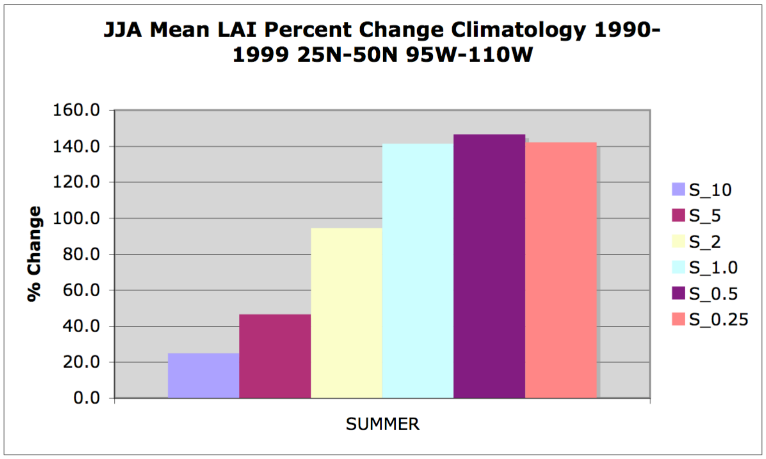


Figure 16. JJA % change of LAI by each forcing.

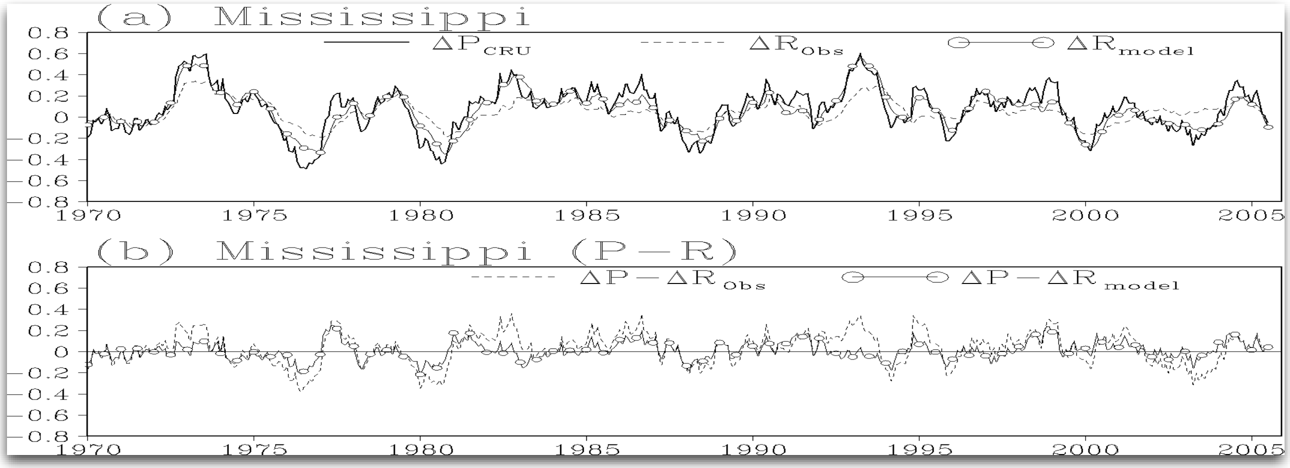


Figure 17. Time series of change in precipitation – change in runoff observation (dashed) compared with change in precipitation – change in runoff modeled by QTCM (solid). *Zeng et al* [2007]

Appendix A1: Digital global map of irrigated areas 1995

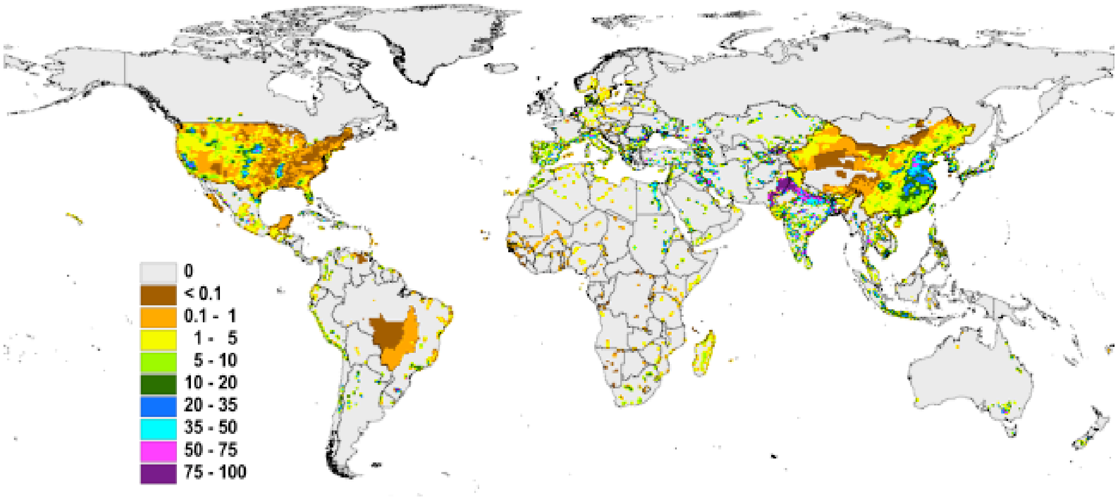


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Fig. A1.1: Digital global map of irrigated areas. Map shows the fraction of the area of each 0.5° by 0.5° cell that was equipped for irrigation in 1995.

Figure 18. Digital global map of irrigated areas. *FAO* [1995]

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