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High resolution modeling of the regional impacts of climate change on irrigation water demand

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Abstract In the Arkansas River Basin in southeastern Colorado, surface irrigation provides most of the water required for agriculture. Consequently, the region's future could be significantly affected if climate change impacts the amount of water available for irrigation. A methodology to model the expected impacts of climate change on irrigation water demand in the region is described. The Integrated Decision Support Consumptive Use model, which accounts for spatial and temporal variability in evapotranspiration and precipitation, is used in conjunction with two climate scenarios from the Vegetation-Ecosystem Modeling and Analysis Project. The two scenarios were extracted and scaled down from two general circulation models (GCMs), the HAD from the Hadley Centre for Climate Prediction and Research and the CCC from the Canadian Climate Centre. The results show significant changes in the water demands of crops due to climate change. The HAD and CCC climate change scenarios both predict an increase in water demand. However, the projections of the two GCMs concerning the water available for irrigation differ significantly, reflecting the large degree of uncertainty concerning what the future impacts of climate change might be in the study region. As new or updated predictions become available, the methodology described here can be used to estimate the impacts of climate change.

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1 Introduction

The Intergovernmental Panel on Climate Change (2001) has stated that increasing amounts of carbon dioxide (CO_2) and other greenhouse gases will raise global temperatures causing what is known as global warming. If global warming occurs as projected, it might have profound impacts on water resources and agriculture.

In the Great Plains of the United States, agriculture is an important economic activity and is the region's main water user. It is estimated that 80% of consumptive use (CU) of water in the arid west of the United States is from agriculture, and irrigated land increased from 3.5 million acres in 1950 to 15 million acres in 1990 (Opie 1996; Solley 1997). The Arkansas River Basin in Colorado has a semi arid climate, and the region's irrigated agriculture relies heavily on surface water supplies. Water shortages plague the region. As competition between urban development and agriculture increases in the region, issues pertaining to water resources are likely to become even more contentious.

The impacts of climate change may further stress the region's water resources by widening the gap between the demand for, and supply of, water for irrigation. The potential impacts of climate change are expected to affect minimum winter temperature, summer average temperature, and rainfall amounts and intensities during the growing season (Baron et al. 1998, 2000). Increased temperatures are expected to alter evapotranspiration (ET) and precipitation, the prime drivers of water availability and agricultural production. These changes in temperature may increase evaporation, resulting in more intensive convective storm activity and water shortages. The lack of available water, due to increased temperatures and evaporation, can deplete soil moisture which can greatly reduce agricultural yield (Rosenzweig and Hillel 1993, 1998; Ojima et al. 1999). Temperature changes are also expected to affect crop communities by changing the length of the growing season (Alward et al. 1999).

Water is a critical component of the socio-economic activities contributing to land transformations. Changes in land use and climate will affect water quantity and quality. Land and water managers operate systems to cope with climate variability. Reliable advance assessments of the impacts of climate change can improve the management of water resources systems. To refine our understanding of the extent and magnitude of climate change, more detailed impact studies are urgently needed. Therefore, details of water budgets and water cycles need to be understood at regional and sub-regional (e.g. river basin) scales, the scales at which integrated water management decisions are made. Regional water budgets need to be quantified so that temporal and spatial distribution of water availability can be better understood. These budgets need to address all components of the water cycle, including water content in the atmosphere, soil and vegetative cover. The interaction between these components needs to be linked to information about current and future climate regimes and made available with high spatial resolution to land and water managers. The research described here provides a modeling methodology for linking irrigation water demand to climate change regimes on monthly and seasonal time scales.

Potential impacts of climate change in river basins have been assessed for years. A number of studies have used projected climate scenarios to assess the risk to water resources from climate change (Lettenmaier et al. 1999; Strzepek and Yates 2000; Sharma et al. 2000). In this study the possible effects of climatic changes on irrigation water demand in the Arkansas River Basin are investigated using the Integrated Decision Support Consumptive Use model (IDSCU 2005) and two transient climate scenarios. The main goal of this research is to improve the estimates of the potential impacts of climate change on irrigation water demand by using higher resolution climate scenarios at smaller temporal and spatial scales of analysis.

2 Description of study area

This study focuses on the Arkansas River Basin in Colorado. The study area is bounded on the west by the Rocky Mountains, on the east by Kansas and by New Mexico and Oklahoma on the south (Fig. 1). The area covers approximately 72,742 km^2 (28,415 square miles). The basin encompasses about 27% of the state of Colorado. The headwaters of the Arkansas River are located near Leadville, at an elevation of over 3,050 m (10,000 ft) above mean sea level. From there, the Arkansas River's elevation drops rapidly until it emerges from the mountains near Pueblo. The river then runs in an easterly direction until it reaches the Colorado–Kansas border near Holly, Colorado at an elevation of about 1,036 m (3,400 ft).

In the Arkansas River Basin, temperature and precipitation vary widely in response to topographic differences. Average annual temperatures range from 2°C at Leadville in the mountains to 12°C at Lamar in the lower valley. Seasonal variations in temperature are very large. The average frost free season (0°C threshold) varies from 85 days at Leadville to 167 days at Canon City.

Precipitation is distributed unevenly throughout the year. Precipitation ranges from 9 to 12 in per year in the middle and eastern parts of the region, 16 to 20 in in the western part, and as much as 45 in in the highest mountain ranges. At high elevations, much of the precipitation occurs as snow. Runoff from this snowfall constitutes the principal water supply for the region, and water supply varies from year to year depending on the amount of winter snowpack in the mountains. In general, more than 60% of the average annual runoff occurs between April and July, with 20% occurring between August and October.

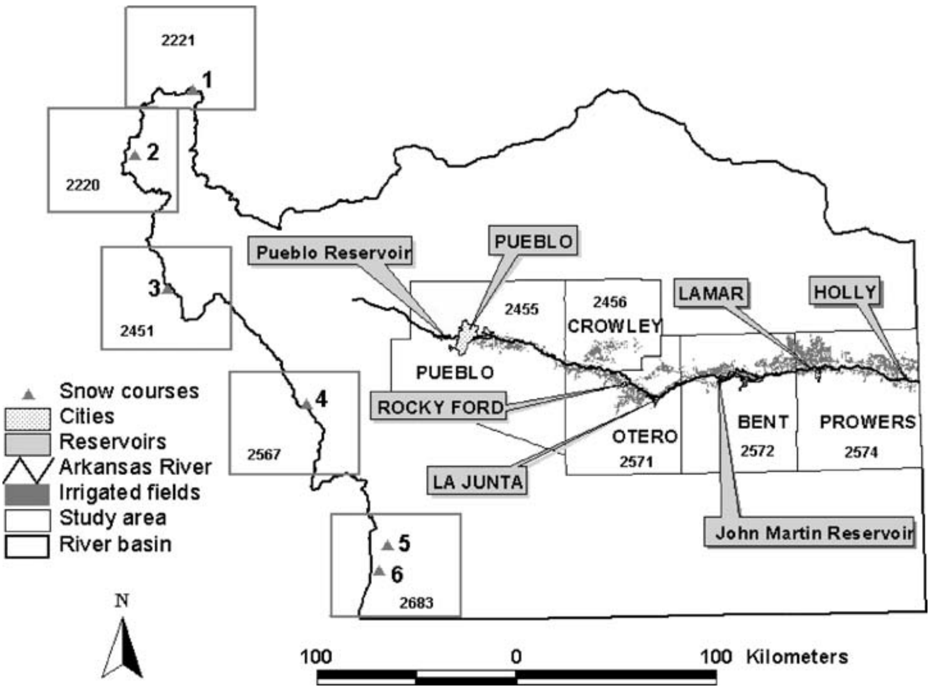


Fig. 1 Features of the study area in the Arkansas River Basin, Colorado

Lakes and reservoirs in the basin serve to store natural runoff, which generally peaks during May or early June, for use when needed. Peak demand for water usually occurs in July and August.

Trans-basin diversions are also a significant addition to the basin water supply. There is an extensive system of canals, tunnels, and reservoirs for collecting and transporting water from the western side of the Continental Divide to the Arkansas River Basin.

Water is applied to crops and pasture in the basin through a huge system of ditches and canals. Twenty of the major canals are included in this study. Table 1 shows the total diversions for those canals being studied. The average amount of water diverted to these systems is 1.07 ha-meters per hectare for 106,436 irrigated hectares (3.5 acre feet per acre for 263,000 irrigated acres) served by 20 canals. The surface diversion data was summarized from records of the Colorado State Engineer's Office in Denver.

3 Methods

The following steps were taken to meet the research objectives:

1. The Arkansas River Basin was selected for study as it is a region with reliable data records that is vulnerable to climate change.
2. The whole river basin was divided into 5 sub-areas corresponding to the climate grid cells.
3. Two climate scenarios with high spatial resolution (0.5×0.5 deg) from the Vegetation-Ecosystem Modeling and Analysis Project (VEMAP) (Kittel et al. 1995) were used. The two scenarios were extracted and scaled down from two general circulation models

Table 1 Total diversions for canals studied

Ditch	Hectares served	Diversions (ha-m)
Bessemer	7,028	7,760
Booth	189	497
Excelsior	875	293
Collier	203	86
Colorado	9,279	10,680
RF Highline	8,020	10,284
Oxford	1,910	3,067
Otero	1,159	838
Catlin	6,943	10,990
Holbrook	5,286	5,274
Rocky Ford	2,184	5,381
Ft Lyon	35,602	29,900
Las Animas	2,637	3,898
Fort Bent	1,768	2,067
Keese	754	660
Amity	15,252	9,890
Lamar Manvel	3,180	5,086
Hyde	499	284
XY Graham	1,764	1,107
Buffalo	1,984	2,437
Total	106,515	7,760

(GCMs), the HAD from the Hadley Centre for Climate Prediction and Research and the CCC from the Canadian Climate Centre.
4. The CU model IDSCU (2005) was modified and applied to simulate irrigation water demand from information about climate, vegetation, and soil. The model-simulations were used to determine the effects of climate change.

3.1 Selection of the region

In developing a database for this kind of research, the basin selected must fulfill a number of criteria required for developing and testing the modeling system. It is especially important that the basin selected encompass an area with a variety of land covers and acreages to reflect the variability in responses to climatic effects and that there are enough climate and crop data records to calibrate the model. The Arkansas River Basin meets these requirements.

3.2 Climate data

The scaled down climate data used in this study was provided by the VEMAP (Kittel et al. 1995). The VEMAP developed climate data sets for the continental United States. The climate data includes historical data from 1895–1993 and projections from two GCM-based scenarios for 1994–2099.

The historical time series were derived from: (a) variable length data records from 1895–1990 (1,200 stations) and (b) short data records from 1951–1990 (6,000–8,000 stations). The two GCM models, the HAD and the CCC, generated future climate data (projections) assuming a progressive 1% annual increase (transient) in atmospheric CO_2 concentrations.

For the VEMAP, the conterminous US was divided into $0.5 \times 0.5°$ grid cells in order to simulate small-scale influences such as local topography and ecosystems on climate (Kittel et al. 1995). As part of the VEMAP project, the National Center for Atmospheric Research processed, spatially interpolated (downscaled), and topographically adjusted the historical and the projected climate data to the 0.5° lat/long VEMAP grid. The downscaling process accounted for the effects of local topography on climate parameters. Projections from the two downscaled GCMs for the study area are shown in Fig. 2.

The study area is composed of 5 counties: Pueblo, Crowley, Otero, Bent, and Prowers (Fig. 1). Each county was represented by a grid cell (cells numbered 2,455, 2,456, 2,571, 2,572, and 2,574 respectively) from the VEMAP grid. Climate and crop data from each grid cell (county) was used to estimate the water demand at the county scale and then integrated to the basin scale.

3.3 The IDSCU model

The IDSCU (2005) was the model used by this study to simulate climate change impacts on irrigation water demand. It was developed by the Integrated Decision Support group, a research group within the Civil and Environmental Engineering Department at Colorado State University (http://www.ids.colostate.edu). IDSCU incorporates monthly and daily methods to estimate ET. The model estimates ET from weather data files and applies crop and area information to determine the CU. The model applies the available water supply and weather data to determine the water use of various crops during the growing season. Surface water supplies can be specified. If there is additional CU beyond the surface

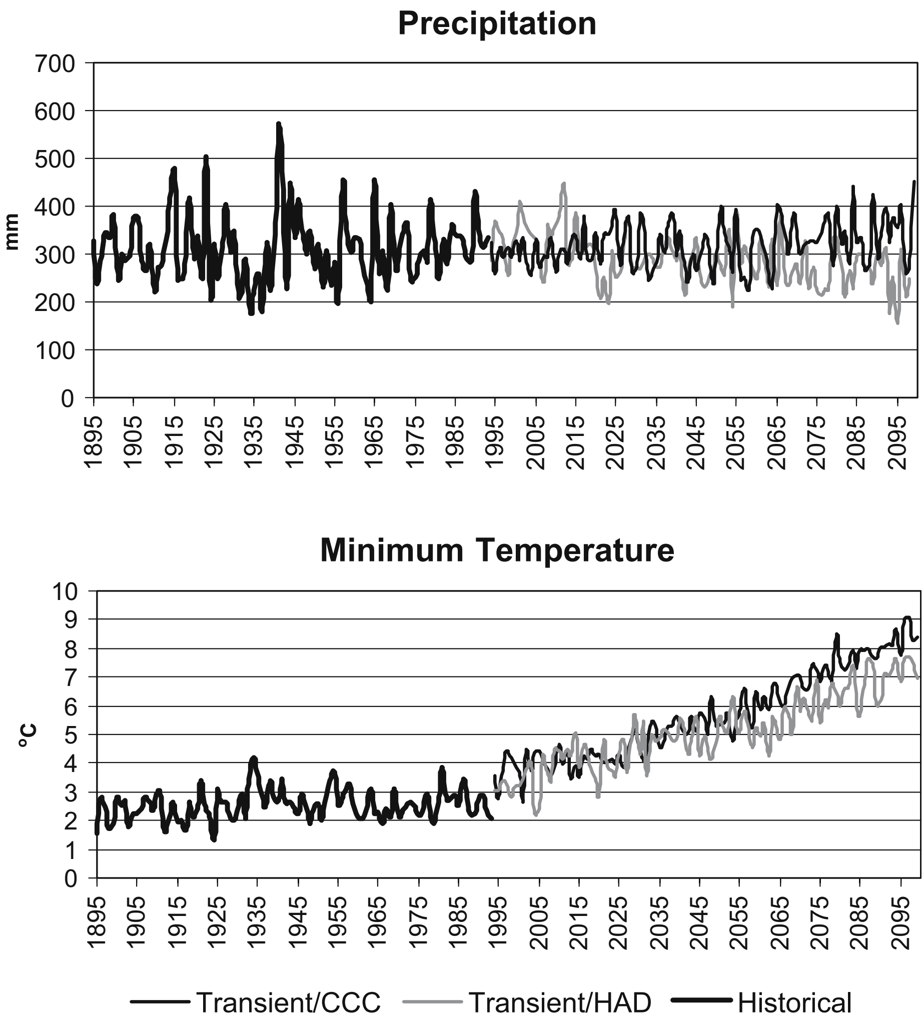


Fig. 2 Time series of annual precipitation and minimum temperature (the figure includes both historical data from 1895–1993, and projections for 1994–2099)

supplies; wells can be assumed to supply the additional CU. Weights can be assigned to weather stations, reflecting their relative influence. The computation of ET includes an option for calculating a soil moisture budget. The model can be used to develop CU scenarios using climate scenarios and crop data. This means that IDSCU is capable of estimating and evaluating the impacts of climate change on irrigation water demand. The model is also flexible enough to be used to project the combined impacts on irrigation demand of global warming and crop physiological responses to elevated atmospheric CO_2.

In this study, ET was estimated on a daily time step using the Penman–Monteith combination method (American Society of Civil Engineers 1990). Maximum and minimum daily temperature, solar radiation, relative humidity, wind speed, and daily precipitation were inputs to the model. IDSCU was run on 5 representative sub-areas and different crop systems to reproduce the spatial complexity of irrigation water demand in the region.

3.4 Model testing and validation

The Penman–Monteith method that was used to estimate ET has already been calibrated under different climatic conditions including the ones that prevail in the study area. Currently several agencies, including an organization whose primary purpose is to collect weather information for agricultural areas in Colorado (the Colorado Agricultural Meteorological Network CoAgMet 2006) uses a very similar method (Kimberly–Penman) to estimate ET in the study area. However, the reference ET (alfalfa) values computed by the model were compared to measured and computed data for the same period of time from different sources to evaluate the accuracy of the ET method used (Table 2). The measured data are part of a project to determine the levels and sources of salinity in the lower Arkansas River Basin (Gates et al. 2006) in which atmometers are used to measure ET values in fields of alfalfa and other crops. The Penman–Monteith model reliably produced results that are in good agreement with the results of the other sources.

4 Results and discussion

The main approach used in this analysis is to compare model predictions to baseline values (historical values under no climate change). The baseline data is a daily climate record from 1960–1990. The scenarios cover the period of time 1895–2099. The main features of these scenarios are presented in the following tables and figures.

Figure 3 shows, in decades, the deviations from the baseline of monthly mean temperatures under the HAD and the CCC scenarios in the Arkansas River Basin. The projections show that the region is expected to be warmer due to climate change. The decade mean temperature increases gradually over time. The 2090s are the warmest decade in the projected time period. The average departure of temperatures from the baseline ranges from 0°C change in the 1990s up to 5°C change in the 2090s for the months presented (April–September). The average rate of temperature change is 0.45°C per decade. Under the CCC scenario, the temperatures in the region are expected to be warmer than under the HAD scenario.

Table 3 presents the projected changes in monthly mean temperatures compared to baseline levels. The statistics in the table are presented in decades to show the trends and the variability in magnitude and direction of the changes. The deviations from the baseline projected by the two scenarios for the region are indications of the magnitude and direction of the climate changes. The temperatures during the winter months are projected to have relatively larger changes than in summer months. The winter temperatures are projected to increase by up to 9°C in January of the 2090s, while for summer, a maximum increase of 5°C is expected in July of 2090s. The large increases in winter temperature projections are attributed to the fact that the winter baseline temperatures are very low. In general, the two GCM scenarios, the HAD and the CCC, show a fair amount of agreement regarding the direction and the magnitude of change in average annual temperature.

Table 2 Comparison of ET values

Source	ET mm (inches)
CoAgMet	1,165 (45.89)
Model (P-M)	1,175 (46.25)
Atmometers	1,135 (44.68)

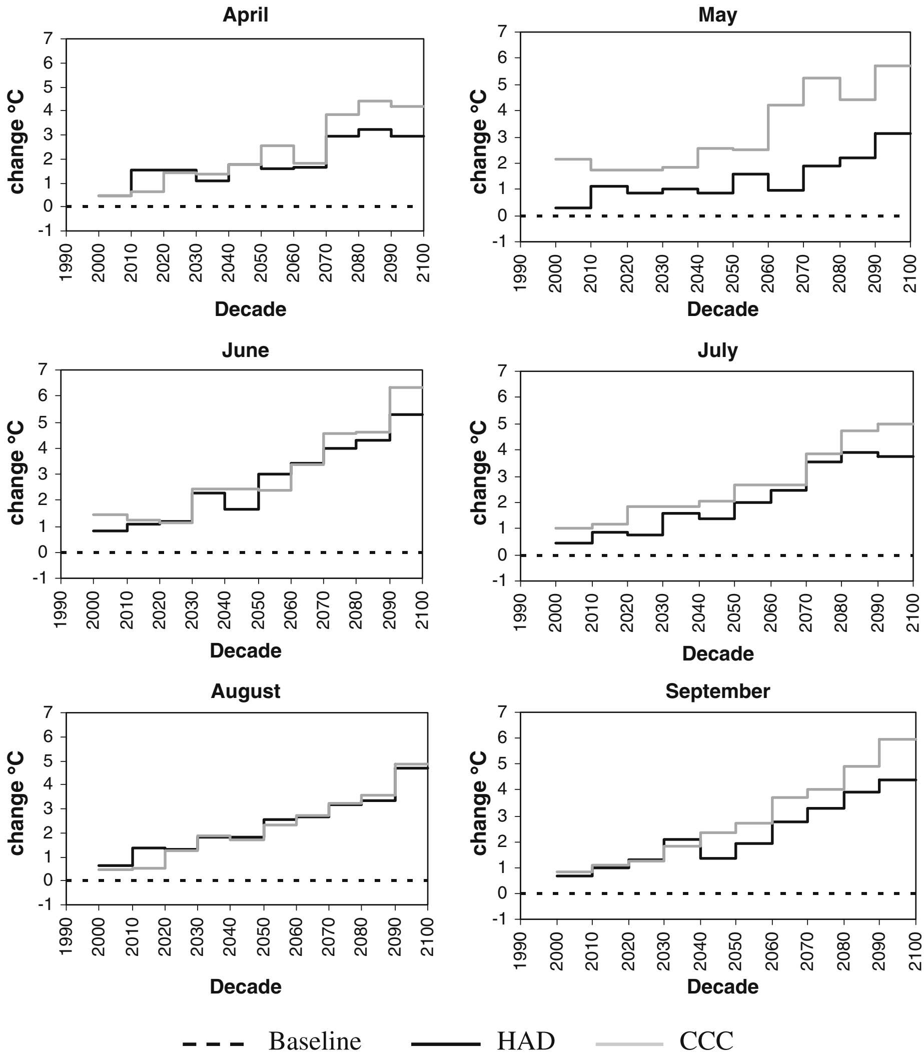


Fig. 3 Change in monthly mean temperature by decade

However, there is very little agreement between the two GCMs concerning the direction and magnitude of change in average annual precipitation. As stated earlier, most of the surface water supply in the Arkansas River Basin comes from the precipitation that falls on the mountains. Table 4 shows the baseline and the changes predicted by the two GCMs in the monthly mean accumulated precipitation in the mountains. The values that are presented in the table are the accumulated precipitation from the beginning of the water year in October to each following month. For example, for April the precipitation amount presented is the accumulated precipitation from October to April.

Figure 4 shows, by decade, the baseline and changes in monthly mean accumulated precipitation under the HAD and the CCC scenarios. It also shows the variability and general pattern of changes in the decade mean precipitation. Under the HAD scenario, precipitation projections show large differences and abrupt changes in decade monthly

Table 3 Monthly baseline temperature and deviations from baseline under the HAD and the CCC scenarios

	Baseline (°C)	1990s (ΔT)	2000s (ΔT)	2010s (ΔT)	2020s (ΔT)	2030s (ΔT)	2040s (ΔT)	2050s (ΔT)	2060s (ΔT)	2070s (ΔT)	2080s (ΔT)	2090s (ΔT)
Oct.												
HAD	3	1	1	1	2	2	2	2	3	4	4	4
CCC		0	1	2	1	1	2	2	4	4	4	5
Nov.												
HAD	−4	−1	1	2	1	1	2	3	2	3	3	4
CCC		−1	1	1	1	1	1	1	2	3	4	4
Dec.												
HAD	−9	0	1	3	3	3	3	4	4	4	6	6
CCC		1	2	3	2	4	4	5	4	5	5	6
Jan.												
HAD	−10	2	3	3	3	5	4	6	4	5	6	9
CCC		2	3	3	4	5	6	6	8	8	9	9
Feb.												
HAD	−7	1	1	3	2	3	4	4	3	4	5	6
CCC		2	2	2	3	4	6	5	6	7	8	9
Mar.												
HAD	−4	1	1	2	2	3	3	3	3	4	5	4
CCC		1	1	1	2	3	3	3	4	4	5	5
Apr.												
HAD	2	0	0	2	2	1	2	2	2	3	3	3
CCC		1	0	1	1	1	2	3	2	4	4	4
May												
HAD	7	0	0	1	1	0	1	2	1	2	2	3
CCC		0	2	2	2	2	3	3	4	5	4	6
June												
HAD	13	1	1	1	1	2	2	3	3	4	4	5
CCC		0	1	1	1	2	2	2	3	5	5	6
July												
HAD	16	0	0	1	1	2	1	2	2	4	4	4
CCC		0	1	1	2	2	2	3	3	4	5	5
Aug.												
HAD	15	0	1	1	1	2	2	3	3	3	3	5
CCC		0	0	1	1	2	2	2	3	3	4	5
Sept.												
HAD	10	0	1	1	1	2	1	2	3	3	4	4
CCC		1	1	1	1	2	2	3	4	4	5	6

mean, but despite the variation in the decade mean, a pattern is apparent. The mean precipitation increases gradually from the 2010s to 2030s with an average rate of increase of 1.4% per decade, decreases in the 2040s and 2050s with an average rate of decrease of 1.0% per decade, and gradually increases from the 2060s to 2090s with an average rate of increase of 2.2% per decade. In general, the HAD scenario projects a wetter climate regime in the region. Precipitation is expected to increase throughout the year with the greatest increase in the winter months. Under the HAD scenario, precipitation increases up to 40% during the winter, 36% during the spring, and 25% over the summer. The highest increase (41%) is projected for February. A 36% increase is projected for April (spring) while the lowest increase (20%) is projected for August (summer).

Table 4 Monthly mean accumulated precipitation, by decade, for baseline climate and percent deviations from baseline for the HAD and CCC scenarios (mountains)

	Baseline (mm)	1990s (%)	2000s (%)	2010s (%)	2020s (%)	2030s (%)	2040s (%)	2050s (%)	2060s (%)	2070s (%)	2080s (%)	2090s (%)
Oct.												
HAD	37	1	−16	−12	3	5	−32	−20	−29	57	6	−1
CCC		−8	−31	−23	−8	−33	−47	−35	−18	−43	−40	−30
Nov.												
HAD	76	2	−18	−7	2	10	−3	−9	−5	36	12	15
CCC		−6	−18	−11	−10	−28	−19	−20	−15	−22	−19	−11
Dec.												
HAD	114	−1	−11	0	3	12	−3	−1	−1	36	33	21
CCC		−8	−8	−9	1	−18	−14	−14	−10	−5	−2	1
Jan.												
HAD	146	0	−9	9	6	22	6	5	5	38	32	40
CCC		−6	−5	−7	0	−12	−8	−12	−5	−4	−1	2
Feb.												
HAD	184	1	−9	10	8	22	13	10	8	37	35	41
CCC		−5	−1	−7	−1	−13	−7	−11	−4	−1	3	5
Mar.												
HAD	236	5	−6	12	8	19	12	10	14	35	34	39
CCC		−1	0	−5	−3	−11	−8	−6	−5	1	7	10
Apr.												
HAD	282	6	−4	10	10	17	13	9	12	32	31	36
CCC		0	0	−3	0	−7	−7	−4	−3	3	10	11
May												
HAD	321	4	−5	9	12	17	10	7	14	29	30	33
CCC		−1	−1	−3	2	−6	−5	−4	−2	1	11	7
June												
HAD	351	1	−5	10	12	15	8	6	15	25	26	31
CCC		−3	−1	−2	0	−2	−5	−4	−2	1	10	6
July												
HAD	401	3	−5	9	8	14	5	3	14	23	23	25
CCC		0	2	2	−2	−2	−5	−1	0	0	11	3
Aug.												
HAD	453	3	−6	5	7	10	0	1	12	21	21	20
CCC		1	4	−1	−3	2	−4	0	−2	−3	6	0
Sept.												
HAD	490	1	−6	4	8	11	0	3	12	22	21	24
CCC		0	5	1	−3	1	−6	−2	−2	−6	7	−1

However, the CCC simulations project a considerably drier climate regime for the region. The projections of the decade mean precipitation are at or below the baseline level except for the 2080s. The variation in the decade mean precipitation is less than that of the HAD with no apparent pattern. Precipitation is projected to decrease throughout the year with the largest changes expected in spring and summer. The 2040s are projected to be the driest decade, with the largest decrease (47%) projected for October. A 7% decrease is projected for April, and the smallest decrease (4%) is projected for August.

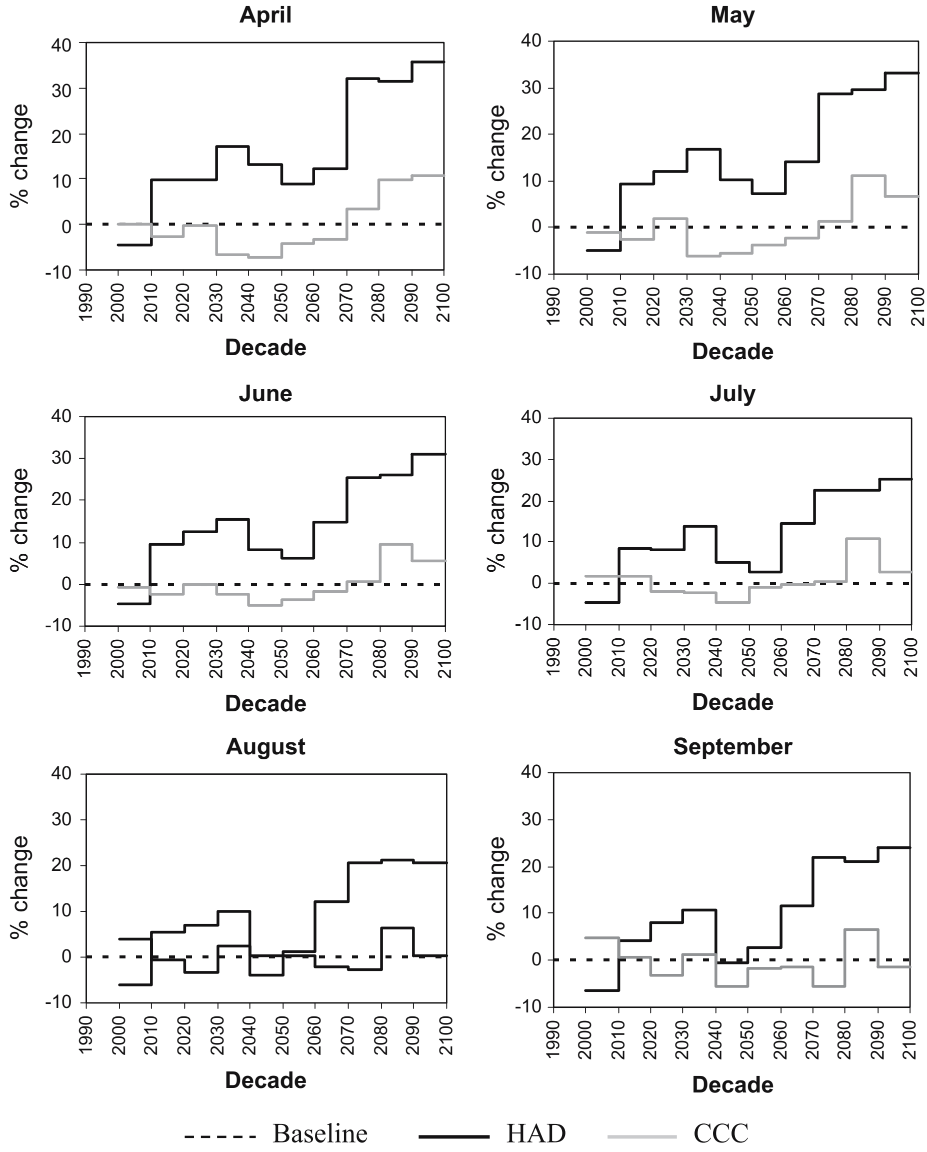


Fig. 4 Percent change in accumulated precipitation by decade: mountains

4.1 Effects on water demand

The effects of climate change on irrigation water demand were explored using the IDSCU model. The model was first used to estimate ET from historical data to provide the baseline data sets. Next, the sensitivity of ET to multi-climatic and plant factors was tested.

4.1.1 ET sensitivity

ET responds differently, in magnitude and direction, to changes in each climatic and plant factor (e.g. temperature, net radiation, humidity, wind speed, leaf area index, and stomatal resistance). For example, an increase in temperature means that air is able to hold more moisture and this by itself would cause evaporation to increase. Some other changes accompanying the changes in temperature, such as the amount of energy available, also impact the evaporation rate. Net radiation, defined as the difference between incoming and reflected solar radiation to and from the earth's surface, provides the energy to change phase in processes important for ET such as soil heat flux, air and vegetation heating (temperature), photosynthesis, and evaporation. Increased concentrations of CO_2 are expected to trap the reflected radiation causing global warming. In general the degree of cloudiness is the factor controlling the amount of incoming radiation to the earth's surface and accordingly the net radiation. In the absence of clouds, high levels of radiation, most likely will increase evaporation, but at some times of the year, cloud cover reduces radiation while temperatures remain high. Generally, higher temperatures tend to decrease humidity, even though atmospheric moisture content might increase due to increased evaporation. However, an increase in humidity or a decrease in solar radiation (increase in clouds) would lead to a decrease in evaporation. Changes in wind speed also affect evaporation rates as well as changes in plant parameters. Therefore, changes in all or some of these factors mentioned above are expected to have an impact on ET.

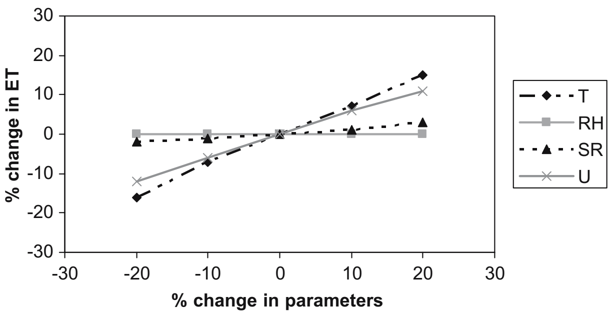
Martin et al. (1989) conducted a sensitivity analysis on ET using the Penman–Monteith formula in a wheat field in Nebraska. Their results showed that ET is highly sensitive to air temperature, solar radiation, humidity, and stomatal resistance. For this study the sensitivity of ET for each climatic factor was analyzed. Figure 5 illustrates the results of the sensitivity analysis. The calculations of ET were made daily. The values presented are an average over the simulation period (100 years). As shown in the figure ET is more sensitive to changes in temperature (T) and wind speed (U) while solar radiation (SR) and relative humidity (RH) have only slight impacts.

In the scenarios studied, the simulations were carried out considering the effects of multi-climate factor changes. The climate scenarios used incorporated changes in all the factors mentioned above as well as changes in precipitation, and the ET estimates obtained are the result of the combined effects of changes in all of these climatic factors.

4.1.2 Effects on ET

The ET analyses assumed that the reference crop alfalfa and all other crops used in this study respond in the same manner to changes in climate and CO_2 (Allen et al. 1991). This

Fig. 5 Predicted ET in response to changes in climatic factors (temperature *T*; relative humidity *RH*; solar radiation *SR*; wind speed *U*)



assumption permitted the use of crop coefficients to estimate each crop's ET while using an alfalfa reference. Mean crop coefficients from the ASCE (1990) were used to estimate actual crop ET values.

This research has emphasized the use of spatial and temporal approaches in the estimation of regional ET which we feel provides additional information that will be valuable to water managers and planners. Grid cells at 0.5° resolution were used to estimate ET. The average of the cells' values was then used to estimate the regional ET. Temporally, the responses of the ET to changes in multi-climatic factors were estimated daily for each crop, and then the daily estimates were aggregated into monthly and seasonal values. Since the length of the growing season was unchanged, climatic changes were the only cause of changes in ET. The influences of climatic changes on monthly and seasonal ET are presented in the following sections. Scale is a key element in the description of the effects of climate change. To better understand the possible impacts of climate change, the ET projections were analyzed at different scales. The results are presented relative to the average seasonal ET estimated from the baseline scenario (1960–1990) in order to give insights into the magnitude and direction of the changes.

4.1.3 Effects of scale

The effects of scale on how change in climate might alter regional irrigation water demand are illustrated in Fig. 6, which represent the changes in estimated average seasonal ET from 1994 to 2099 at different scales. The ET was estimated twice based on a climate scenario at two different scales. The first scale used the climate variables generated by the British Hadley GCM (HADCM2) at 3.7° × 2.5° resolution, and for the second scale (HAD) used the climate variables downscaled from the HADCM2 outputs to 0.5° resolution. Regarding the direction of the effects of climate change, there is an increasing trend in the values of ET among the different scales and this is attributed to the dominant effect of the increasing temperature. Regarding the magnitude of the effect of climate change, the ET projections are clearly different.

At the basin-scale (Arkansas River Basin) the ET projections were estimated using climatic data from the grid cell that the study area falls in at the 3.7×2.5° resolution. As shown in Fig. 6 the ET projections are very low compared to the baseline ET values estimated locally. These results indicate that, at this scale, weather conditions critical to the accurate simulation of ET are not properly represented when using data with this resolution.

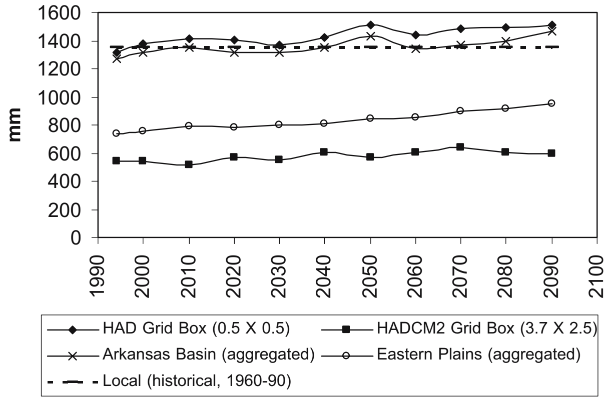


Fig. 6 Seasonal ET under climate change by decade at different scales

This supports what has already been established that the low resolution of the GCMs limits their abilities to reproduce the actual complexities existing at some locations where there are significant orographic changes or other factors. This is due to the representation of the weather conditions on a large scale smoothing out heterogeneities that exist at a local or elementary scale that can have significant impact on ET rates.

At the sub-basin scale, at 0.5° resolution, the ET projections estimated using the scaled down climatic data are higher and more comparable to the baseline ET values than the ET projections estimated using climatic data at the 3.7×2.5° resolution. This implies that the projections of the climate data at the scaled down resolution are carrying some of the heterogeneities of the local scale and reasonably represent the weather conditions that are suitable for reasonable simulation of the ET for the study area. As shown in Fig. 6 the projected ET values are higher than but are relevant to the baseline values which were basically estimated at the local scale and aggregated to the basin scale. Therefore, to determine how climate change would affect the irrigation water demand at scales relevant for water planning and management such as basin-scale, we chose to aggregate the ET projections from smaller units to basin-wide scale.

The estimates of the ET projections for the Arkansas River Basin and the eastern plains were derived from the aggregation of the ET projections at the 0.5° resolution cells. The ET estimates for the Arkansas River Basin, as expected, due to the aggregation process are lower than the estimates for the 0.5° resolution cells but they are still comparable. The ET estimates for the Arkansas River Basin are higher than those for the eastern plains because it was generated by aggregating a number of cells some of which are much higher than those used in generating the ET for the eastern plains.

Climatic data is highly variable both temporally (e.g. daily, monthly, and yearly basis) as well as spatially, temperature and wind vary within distances of only a few miles. To show the effect of this spatial and temporal variability on ET, Fig. 7 shows the projections of ET along the gradient of the Arkansas River. The results are presented by cell (county), starting from upstream (Pueblo County), to downstream (Prowers County). The different values of the ET estimates indicate the spatial variability along the gradient of the Arkansas River. The ET values are relatively low at the higher elevation in Pueblo County and increase

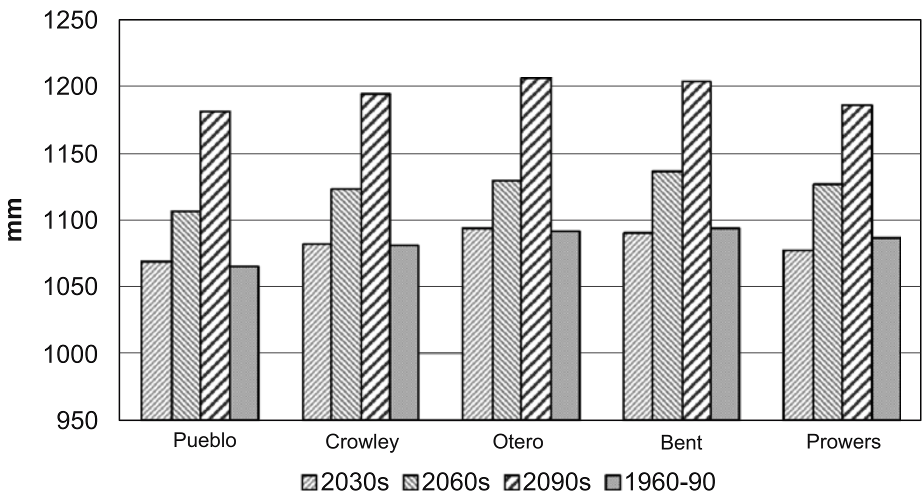


Fig. 7 Projections of ET along the gradient of the Arkansas River Basin

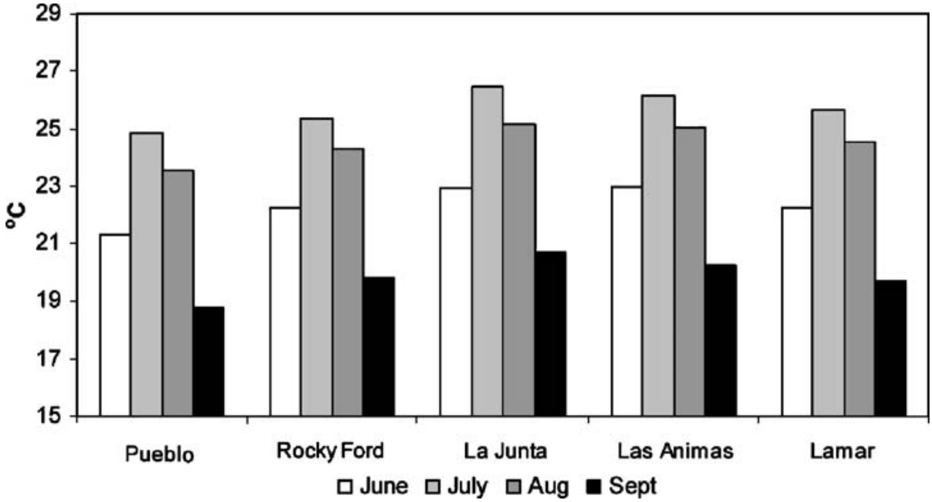


Fig. 8 Temperature distribution along the gradient of the Arkansas River Basin (average 1960–1990)

along the gradient of the basin until Bent County and start to decrease again at the end at Prowers County. This pattern in the projected ET follows the historical pattern of the ET presented as a baseline. This historical pattern of ET has been mainly driven by the pattern of the temperature in this region as shown in Fig. 8. The decrease in the temperature at the lower end of the river basin has been attributed to the windy weather in this area. The cooling effect of the wind causes the temperature to drop and therefore the reduction in ET.

4.1.4 Effect of GMC's scenarios

Climate models projections vary widely depending on the assumptions about the future emission scenarios and how the models incorporate factors such as cloud cover and ocean and land surface characteristics. Due to the uncertainties associated with each GCM model we selected two well accepted models to evaluate what the results of the models would be. Figure 9 shows changes in estimated seasonal ET from 1994 to 2099 for the study region based on the climate projections of the two GCMs. The two climate models are the Canadian Climate Center model (CGCM1) with a spatial resolution of 3.7×3.7° and the Hadley Center model (HADCM2) with a spatial resolution of 3.7° × 2.5°. The figure shows

Fig. 9 Seasonal ET under climate change by decade (low resolution)

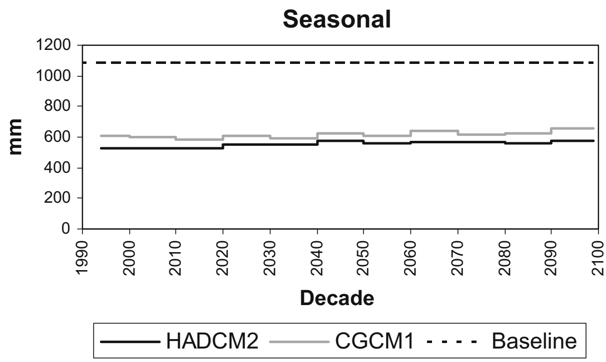


Table 5 Percentage change in monthly ET from baseline

	April (baseline 10 mm)		May (baseline 120 mm)		June (baseline 234 mm)		July (baseline 268 mm)		August (baseline 250 mm)		September (baseline 126 mm)		Season (baseline 1,083 mm)	
	HAD %	CCC %	HAD %	CCC %	HAD %	CCC %	HAD %	CCC %	HAD %	CCC %	HAD %	CCC %	HAD %	CCC %
1990s	−27	49	3	17	3	0	−11	−15	−7	−10	10	4	−2	−4
2000s	92	211	15	46	−3	3	−10	−14	−6	−12	7	−8	0	−1
2010s	121	136	23	31	−2	0	−12	−15	−3	−10	3	−2	2	−3
2020s	81	284	10	44	−3	3	−9	−7	−5	−4	3	1	0	5
2030s	7	260	9	53	−1	5	−10	−10	−1	−8	5	−1	0	4
2040s	70	389	22	61	2	7	−11	−8	0	−7	5	3	4	8
2050s	240	512	52	62	5	4	−11	−6	−5	−10	−3	1	8	8
2060s	61	475	23	77	0	10	−10	−9	−2	−8	5	1	3	10
2070s	240	897	31	95	1	7	−6	0	−6	−13	2	2	6	17
2080s	240	739	32	79	3	9	−7	−6	−7	−9	4	1	7	14
2090s	289	1,116	45	103	4	10	−7	−1	−2	−13	3	4	10	22

that there is significant discrepancy in the GCMs outputs as how climate change might affect the ET in this region. As shown in the figure the ET projections estimated based on the HADCM2 are very low compared to those estimated based on the CGCM1. As indicated by the ET projections at the coarse scale, both models project an increase temperature towards the end of this century, with the CGCM1 projecting a relatively warmer climate.

Using the scaled down scenarios from these two GCM outputs (HAD, and CCC) to assess the impacts that climate change might have on the ET in the study area significant differences between the models were obtained. Table 5 and Figs. 10 and 11 show the changes in seasonal and monthly ET under the two scaled down transient scenarios (CCC and HAD) for the study region between 1994 and 2099. These figures show the changes in decade mean ET for the whole season and each month of the growing season. It is very clear in the figures that the effects of the changes in climate influenced both monthly and seasonal ET. There is a gradual increase in the ET values that can be attributed to the influence of increasing temperatures. The projected changes in ET under the CCC scenario

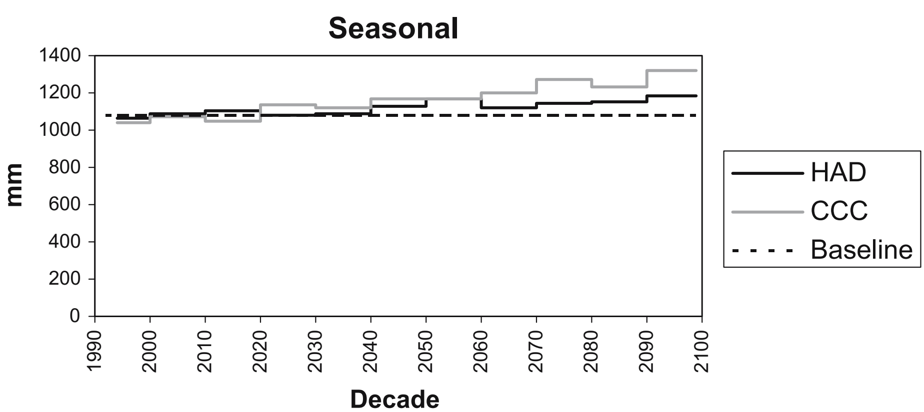


Fig. 10 Seasonal ET under climate change by decade (high resolution)

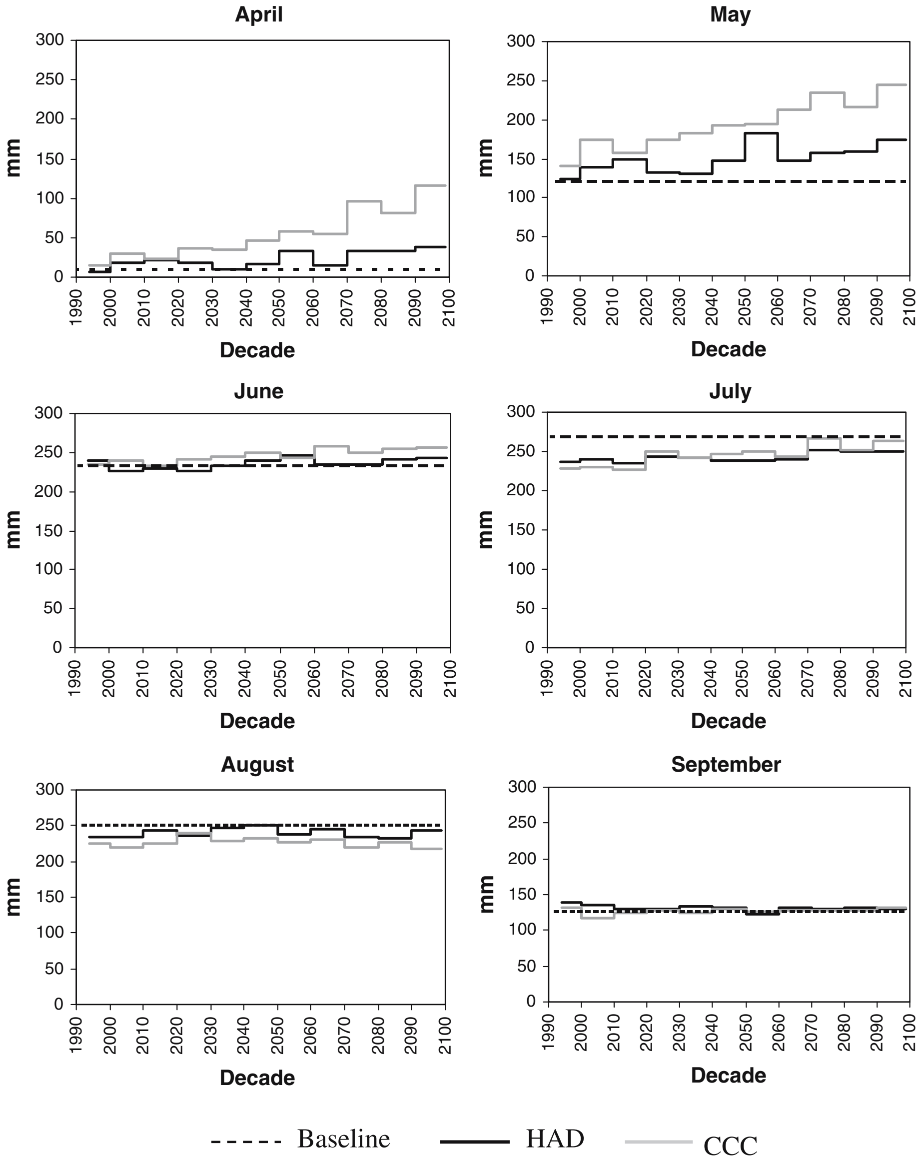


Fig. 11 Variation in monthly ET under climate change by decades

are larger than those under the HAD, primarily due to the higher temperatures projected by the CCC scenario.

According to the CCC scenario, the seasonal ET increases from values below the historical level and crosses the threshold of the historical level in the 2020s. These increases range from 5% above the historical level in the 2020s up to 22% in the 2090s with a rate of increase of 2.6% per decade. Under the HAD scenario, it takes up to the 2040s for ET to cross the threshold of the historical level,; ET gradually increases up to 10% above the baseline in the 2090s at a rate of 1% per decade.

As shown in Fig. 11, changes in monthly ET are more vigorous than those in seasonal ET. It can be observed in the figure that season changes in ET occur between the spring (April–May) and summer months (June–July), changes within the spring months are more vigorous than during the summer months. However, under both scenarios (HAD and CCC) ET is projected to increase above the baseline during the spring months and decrease below the baseline during the summer months. According to the CCC scenario, the increases in ET during the spring (May) range from 30% above the historical level in the 2010s up to more than 100% in the 2090s with a rate of increase of 8% per decade. Under the HAD scenario, ET increases by 12% in the 2010s and by 45% in the 2090s at a rate of increase of 4.5% per decade. These large increases in ET in the spring are attributed to the fact that they were estimated from very low historical (baseline) ET values. During the summers, even though ET is projected to fall below the historical average (baseline), a very slight increasing trend can be detected. Under the CCC scenario ET is projected to increase by 14% in the period from the 2010s to the 2090s at a rate of increase of 1.5% per decade, while under the HAD scenario for the same period of time, ET is projected to increase only by 5% with a 0.6% rate of increase per decade.

Based on this analysis there are several points that need to be emphasized. Despite decade-to-decade variability, a trend in ET changes can be identified. It is very clear that toward the end of the century, ET values increase over time following the trend of temperature. As shown in Fig. 7, the rate of change of ET in the summer is less than that in the spring. ET in the summer tends to increase by smaller amounts than in the spring because the wind speed is lower and the relative humidity is higher during the summer than during the spring. During the spring the changes in ET relative to the baseline are higher than those in the summer because the relative change in temperature is higher in the spring than in the summer. In the summer months ET is projected to go below the baseline in July and August but shows almost no change in June. The low projections of ET in the summer are attributed to the limited amount of water available for evaporation during the summer as a result of high humidity levels and low wind speed. Figure 7 shows that the deviations of projected ET from the baseline were larger under the CCC scenario than under the HAD scenario. This is attributed to the effect of higher temperatures projected by the CCC scenario compared to those projected by the HAD scenario.

Figure 10 shows that seasonal ET increased above the baseline under both scenarios, although the ET values during the summer were relatively low. This is interpreted to mean that the increase in ET during the spring was high enough to offset the decrease during the summer which results in an increase in seasonal ET. Due to warmer and drier climate, projected increases in seasonal ET under the CCC scenario are almost double those under the HAD scenario.

4.2 Effects on irrigation water requirement

Projected changes in irrigation water requirement (IWR) (defined as ET minus effective rainfall, Re) are presented in this section. Table 6 shows the percentage changes in IWR under the two climate change scenarios. Percentage changes in IWR were very high in April and May due to very low baseline values. Large changes in precipitation patterns caused large variation in IWR. In general, the projected increases in IWR were higher than ET under the CCC scenario. This is attributed to the effect of drier conditions projected by the CCC scenario. Under the two scenarios, July and August experienced a decrease in both ET and IWR and this is attributed to very high baseline values for both, but both months showed an increasing trend towards the end of the 21st century when conditions are

Table 6 Percentage change in monthly and seasonal IWR from baseline

	April		May		June		July		August		September		Seasonal	
	HAD %	CCC %	HAD %	CCC %	HAD %	CCC %	HAD %	CCC %	HAD %	CCC %	HAD %	CCC %	HAD %	CCC %
1990s	−29	0	5	17	4	1	−13	−19	−7	−11	11	4	−2	−5
2000s	98	200	15	46	−5	3	−12	−15	−6	−13	6	−10	0	−2
2010s	123	135	22	32	−2	−1	−13	−17	−2	−9	4	−4	2	−4
2020s	78	289	9	45	−5	5	−8	−7	−6	−2	2	0	−1	6
2030s	5	259	8	56	−2	4	−11	−10	0	−10	4	−2	0	3
2040s	72	393	24	61	3	8	−12	−8	3	−7	5	3	5	8
2050s	228	519	53	65	5	4	−11	−9	−4	−9	−5	0	7	8
2060s	59	476	23	79	−1	12	−11	−11	−2	−5	4	2	2	11
2070s	234	911	31	102	1	9	−5	0	−7	−10	0	3	5	19
2080s	228	749	31	82	3	12	−7	−9	−9	−7	3	0	6	15
2090s	280	1,148	45	112	4	12	−7	−1	−2	−12	0	5	9	24

projected to be drier (Fig. 11). Generally, several decades show very little difference in the percentage change in ET and IWR, but under drier conditions the percentage change in IWR was slightly higher than those for ET. For example, during the decade of the 2090s, the projected changes, under the CCC scenario, in seasonal IWR show an increase of 24% while ET increases by 22%.

Based on this analysis, under the two climate scenarios applied, seasonal ET and IWR are expected to increase gradually towards the end of this century. Climatic changes are expected to increase ET and IWR during spring months (April and May) and decrease them during summer months (July and August). Even though there were variations in the changes in monthly projections of IWR, an increasing trend is noticeable. This is due to the influence of temperature which is projected to gradually increase toward the end of this century.

5 Summary

Even though there are differences in the projections of the two models, some patterns of the likely impacts of climate change on irrigation in the study area were shown. The differences in estimated changes in water demand (driven by temperature) primarily are related to differences in estimated changes in temperature. While the two models are in general agreement in the direction of change in temperature they differ in the magnitude of change.

The paper used these two scenarios to explore the following:

- Possible changes in water demand under climate change in the study area.
- Issues of scale in modeling climate changes and their effect on assessment of climate change impacts.
- The effects of scaling down the low resolution outputs of the GCMs on the magnitude of impacts of climate change on ET and IWR.

By scaling down the model results a better understanding of the spatial and temporal distribution of water demand was achieved. Regarding the magnitude of the effect of climate change on water demand in the region, results from the GCM HADCM2 (3.7×2.5°) showed a small change compared to the baseline. This indicates that water demand is exceptionally insensitive to the changes in climate variables generated at this scale, and the range of uncertainty here is too large to be of value to water planners and managers. Narrowing the range of expected changes in climatic and hydrologic variables requires information at finer scales.

At the sub-basin scale (0.5° resolution), IWR or water demand was shown to be very sensitive to changes in climate variables. Driven mainly by changes in temperature, the results show a significant increase in ET above the baseline level. During the periods that precipitation is projected to decrease the impacts on IWR are even more severe. Projections at this scale provide hydrologic information relevant for water planning and management. Farmers can use information about the expected impacts to take actions to mitigate or adapt to the impacts. For example, increased irrigation demand may lead to wide-spread adoption of a more scientific approach to irrigation scheduling, adjustment of yield targets to match available water, and /or the change of cropping patterns.

The analyses presented above at the basin scale suggest that IWR is projected to increase during spring months under both the HAD and CCC climate change scenarios. Increases are very high compared to the baseline level and this can be attributed to an increase in the amount of water available for evaporation as a result of changes in the precipitation regime in the region. Projected increases in air humidity and decreases in solar radiation, due to a projected increase in clouds, under the two scenarios reduced the amounts of IWR to a level below the baseline during some summer months. The projections also show that IWR during the whole season is expected to increase under both scenarios. The net result is that high increases of IWR during spring months offset the decreases of IWR during summer months and the overall effect is that the IWR for the whole season is projected to increase. The information obtained from the monthly time scale, is expected to be very helpful to river basin managers and farmers in developing short and long term strategies to cope with climate change and to assess different actions that could be taken to mitigate or adapt to the possible impacts of climate change. For example, application of crop management practices that enhance soil moisture, understanding the capabilities of the current reservoirs in supplying agricultural areas with water as well as providing flood control, and evaluation of any additional structural requirements and /or reservoir management changes necessary to adapt to new climatic conditions.

The analyses presented above for the Eastern Plains of Colorado suggest that aggregating results to represent the impacts at larger spatial scale smoothes out the information provided at the smaller scale and might be of limited value for water managers.

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References

Allen RG, Gichuki FN, Rosenzweig C (1991) CO2-induced climatic changes and irrigation requirements. J Water Resour Plan Manage 117(2):157–178

Alward RD, Detling JK, Milchunas DG (1999) Grassland vegetation changes and nocturnal global warming. Science 283(5399):229–231

American Society of Civil Engineers (ASCE) (1990) Manual no. 70, evapotranspiration and irrigation water requirements. ASCE, Reston

Baron JS, Hartman MD, Kittle TGF, Band LE, Ojima DS, Lammers RB (1998) Effects of land cover, water redistribution, and temperature on ecosystem processes in the South Platte Basin. Ecol Appl 8:1037–1051

Baron JS, Hartman MD, Band LE, Lammers RB (2000) Sensitivity of a high elevation rocky mountain watershed to altered climate and CO_2. Water Resour Res 36:89–99

Colorado Agricultural Meteorological Network (2006) CoAgMet crop water use (ET) access. http://ccc.atmos.colostate.edu/~coagmet/extended_etr_form.php

Gates TK, Garcia LA, Labadie JW (2006) Toward optimal water management in Colorado's lower Arkansas river valley: monitoring and modeling to enhance agriculture & environment. Colorado Agricultural Experiment Station, Technical Report TR-6-10

IDSCU (2005) Integrated decision support consumptive use model. Version 3.1.20. Colorado State University, Fort Collins

Intergovernmental Panel on Climate Change (IPCC) (2001) Climate change 2001: The scientific basis—Summary for policy makers and technical summary for the working group 1 report. Cambridge University Press, Cambridge

Kittel TGF, Rosenbloom NA, Painter TH, Schimel DS, VEMAP Modeling Participants (1995) The VEMAP integrated database for modeling United States ecosystem/vegetation sensitivity to climate change. J Biogeogr 22:857–862

Lettenmaier DP, Wood AW, Palmer RN, Wood EF, Stakhiv EZ (1999) Water resources implications of global warming: A U.S. regional perspective. Clim Change 43:537–579

Martin P, Rosenberg NJ, Mckenney MS (1989) Sensitivity of evapotranspiration in a wheat field, a forest, and a grassland to changes in climate and direct effects of carbon dioxide. Clim Change 14:117–151

Ojima D, Garcia L, Elgaali E, Miller K, Kittel TGF, Lackett J (1999) Potential climate change impacts on water resources in the great plains. J Am Water Resour Assoc 35(6):1443–1454

Opie J (1996) Does its history doom the plains to failure? Putting chaos theory to work. In: Bruce C, Triplett L (eds) The great plains symposium 1996: The Ogallala Aquifer: sharing the knowledge for the future. The Great Plains Foundation, Overland Park, pp 5–18

Rosenzweig C, Hillel D (1993) The Dust Bowl of the 1930s: analog of greenhouse effect in the Great Plains. J Environ Qual 22(1):9–22

Rosenzweig C, Hillel D (1998) Climate change and the global harvest: potential impacts of the greenhouse effect on agriculture. Oxford University Press, New York

Sharma KP, Vorosmarty CJ, Moore B III (2000) Sensitivity of the Himalayan hydrology to land-use and climatic changes. Clim Change 47:117–139

Solley WB (1997) Estimates of water use in the Western United States in 1990 and water use trends 1960–90, report to the Western Water Policy Review Advisory Commission in Denver Colorado. National Technical Information Service, Springfield, p 19

Strzepek KM, Yates DN (2000) Response and thresholds of the Egyptian economy to climate change impacts on the resources of the Nile River. Clim Change 46:339–356