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Simulating the Potential Effects of Climate Change in Two Colorado Basins and at Two Colorado Ski Areas

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ABSTRACT: The mountainous areas of Colorado are used for tourism and recreation, and they provide water storage and supply for municipalities, industries, and agriculture. Recent studies suggest that water supply and tourist industries such as skiing are at risk from climate change. In this study, a distributed-parameter watershed model, the Precipitation-Runoff Modeling System (PRMS), is used to identify the potential effects of future climate on hydrologic conditions for two Colorado basins, the East River at Almont and the Yampa River at Steamboat Springs, and at the subbasin scale for two ski areas within those basins.

Climate-change input files for PRMS were generated by modifying daily PRMS precipitation and temperature inputs with mean monthly climate-change fields of precipitation and temperature derived from five general circulation model (GCM) simulations using one current and three future carbon emission scenarios. All GCM simulations of mean daily minimum and maximum air temperature for the

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East and Yampa River basins indicate a relatively steady increase of up to several degrees Celsius from baseline conditions by 2094. GCM simulations of precipitation in the two basins indicate little change or trend in precipitation, but there is a large range associated with these projections. PRMS projections of basin mean daily streamflow vary by scenario but indicate a central tendency toward slight decreases, with a large range associated with these projections.

Decreases in water content or changes in the spatial extent of snowpack in the East and Yampa River basins are important because of potential adverse effects on water supply and recreational activities. PRMS projections of each future scenario indicate a central tendency for decreases in basin mean snow-covered area and snowpack water equivalent, with the range in the projected decreases increasing with time. However, when examined on a monthly basis, the projected decreases are most dramatic during fall and spring. Presumably, ski area locations are picked because of a tendency to receive snow and keep snowpack relative to the surrounding area. This effect of ski area location within the basin was examined by comparing projections of March snow-covered area and snowpack water equivalent for the entire basin with more local projections for the portion of the basin that represents the ski area in the PRMS models. These projections indicate a steady decrease in March snow-covered area for the basins but only small changes in March snow-covered area at both ski areas for the three future scenarios until around 2050. After 2050, larger decreases are possible, but there is a large range in the projections of future scenarios. The rates of decrease for snowpack water equivalent and precipitation that falls as snow are similar at the basin and subbasin scale in both basins. Results from this modeling effort show that there is a wide range of possible outcomes for future snowpack conditions in Colorado. The results also highlight the differences between projections for entire basins and projections for local areas or subbasins within those basins.

KEYWORDS: Watershed models; Snowpack; Climate

1. Introduction

Tourism that results from abundant recreational options in Colorado's mountains is often the largest source of revenue for the local community (Gunnison Country Chamber of Commerce 2011; Steamboat on the Move 2011). Many recreational activities, such as fishing, whitewater boating, snowmobiling, and skiing, are directly dependent on water resources, specifically snowpack and snowmelt. The mountainous areas used for tourism and recreation also provide the water supply for more urbanized areas in Colorado and other states. Recent studies, however, suggest that tourism and skiing in particular are at risk from climate change (Aspen Global Change Institute 2006; Williamson et al. 2008).

Projections of future climatic conditions are needed to determine the potential effects of climate change on Colorado's water resources. General circulation model (GCM) simulations of future climate through 2099 project a wide range of possible scenarios (Alley et al. 2007). Local stakeholders, from ski area operators and fishing guides to water supply managers, would like to know if the future will be "the best of times. . .the worst of times. . .the winter of despair" (Dickens 1859) for Colorado's snowpack. Much of what is presented by the popular media would suggest that they should prepare for despair (e.g. Minard 2009).

The objective of the research described in this paper is to demonstrate the utility of a distributed-parameter watershed model for simulating the effects of climate

change on hydrologic conditions at basin and subbasin scales. The research is intended to highlight the range of possible outcomes for future hydrologic conditions in two Colorado basins. We use ski areas located within each of these basins as an example of subbasin scale here, but this type of analysis can be done for any local area and hence is an important tool for water suppliers and other stakeholders. The work was conducted in coordination with several other related studies (Hay et al. 2011; Markstrom et al. 2011).

1.1. Expected changes in mountain snowpack

Winter snowpack in Colorado (and much of the western United States) provides the storage for water used throughout the state during the rest of the year (Serreze et al. 1999; Stewart et al. 2004). An analysis of snowpack water equivalent (SWE) for 1 April 1900–2008, in the western United States, indicated that SWE was lower than average during 1980–2008 (and during several earlier periods) (McCabe and Wolock 2009). Lower than average snowpack water equivalent after 1980 was driven by widespread increases in temperature in western states (Milly et al. 2008; Mote 2006). Temperature increases also are changing the timing of snowmelt. Shifts toward earlier snowmelt and runoff were observed in 1948–2000 data at sites across the western United States, a trend that is projected to continue with increasing temperatures (Stewart et al. 2004). These reported impacts for the western United States may not be fully observed in the mountains of Colorado because of higher elevations and colder temperature as compared to the western United States as a whole. However, substantial shifts in the timing of snowmelt and runoff toward earlier in the year were observed in Colorado in 1978–2007 data (Clow 2010). Factors other than temperature such as changes in snowpack albedo related to dust loading can also affect the timing of snowmelt and runoff (Painter et al. 2010).

1.2. Study areas

Two basins in Colorado were modeled: the East River at Almont, Colorado, and the Yampa River at Steamboat Springs, Colorado (Figure 1). The basins are mountainous, and their streamflows are strongly dependent on the formation of a snowpack in the winter months and the timing of snowmelt in spring and summer. In many ways, these basins are representative of other snowmelt-dominated, high-elevation basins in Colorado that supply much of the water to downstream users. Projected increases in population within these two basins are expected to result in increases in domestic and industrial water use (Colorado Water Conservation Board 2006a; Colorado Water Conservation Board 2006b).

1.2.1. The East River

At Almont [U.S. Geological Survey (USGS) gauging station 09112500] is a tributary to the Gunnison River, which is an important source of water to the Colorado River (Ugland et al. 1991; Spahr et al. 1999). The 750-km^2 basin ranges in elevation from 2440 to 4350 m and has a mean elevation of 3099 m. Current and projected total water demand (total amount of water removed from the river, some of which is returned to the river when not consumptively used) in the Gunnison

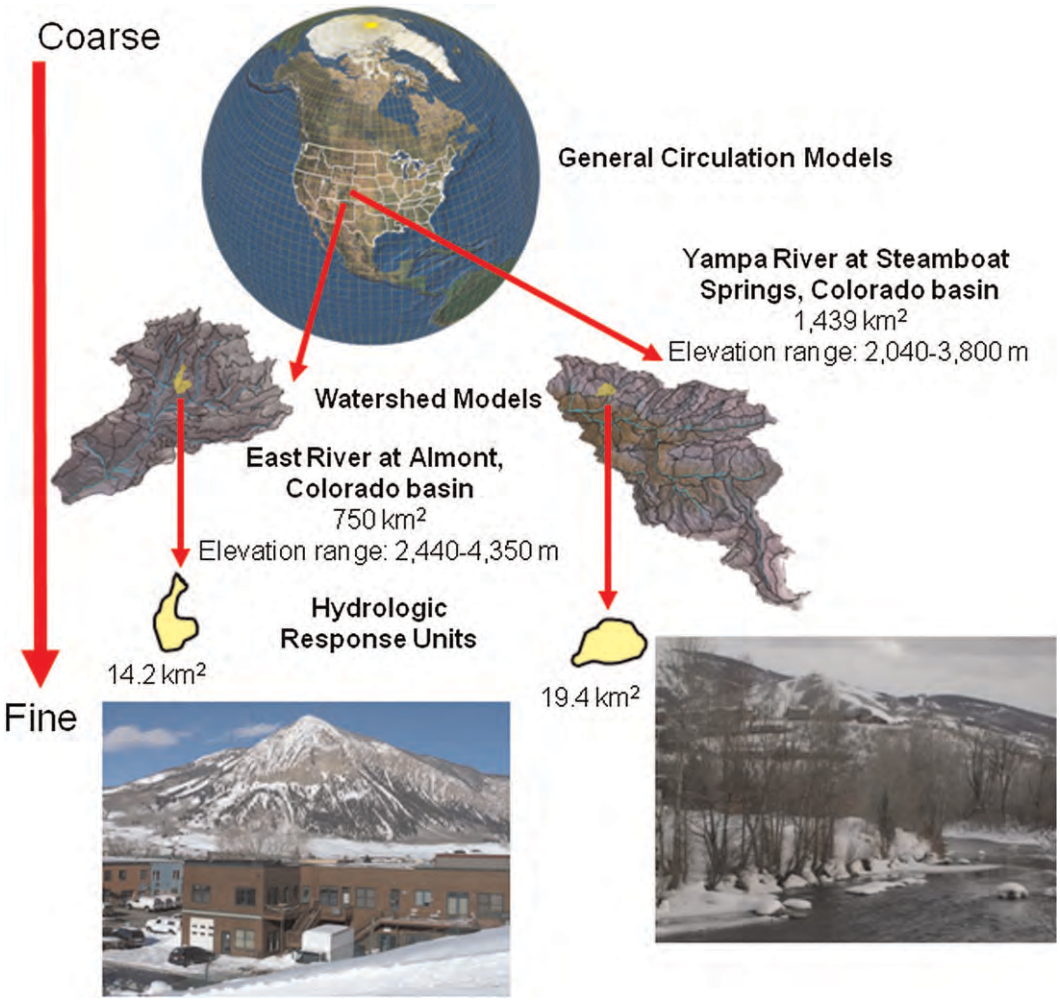

Figure 1. General methodology used for assessing the range of potential effects of climate change on Colorado snowpack in river basins and smaller HRUs.

River basin is about equal to the native supply (undepleted, unregulated available surface water) (Colorado Water Conservation Board 2002a). Irrigation and municipal supply (2000 estimates) are the two largest uses of water within the Gunnison River basin. Tourism is the largest source of revenue in the region (Gunnison Country Chamber of Commerce 2011), and many of the tourist activities, such as fishing, whitewater boating, snowmobiling, and skiing, are directly dependent on the basins' water resources. Crested Butte ski area is located within the East River basin at a base elevation of ~2850 m and a summit elevation of ~3700 m. In the 1990s, the USGS conducted studies to determine the effects of potential climate change on the water resources of the East River basin (Leavesley et al. 1992; Hay et al. 1993; McCabe and Hay 1995). The calibrated Precipitation-Runoff Modeling System (PRMS) model from these studies was used as the starting point in this investigation.

1.2.2. The Yampa River

At Steamboat Springs (USGS gauging station 09239500) is a tributary to the Green River, which is also an important tributary of the Colorado River. The 1439-km^2 basin ranges in elevation from 2040 to 3800 m and has a mean elevation of 2674 m. This gauging station was included in the Hydro-Climatic Data Network, indicating that streamflow records prior to 1987 are relatively ''unaffected by artificial diversions, storage, or other works of man in or on the natural stream channels or in the watershed'' (Slack and Landwehr 1992). The Yampa River basin is one of only a few in Colorado where current and projected total water demand is less than the native supply (Colorado Water Conservation Board 2002b). Irrigation and livestock (1995 estimates) are the two largest uses of water within the Yampa River basin. Tourism is the largest source of revenue in the region (Steamboat on the Move 2011), but agriculture also is important. As in the East River basin, many tourist activities are dependent on water resources. The Steamboat ski area is located within the Yampa River basin at a base elevation of ~2200 m and a summit elevation of ~2770 m. In the 2000s, the USGS conducted studies to determine the effects of potential climate change on the water resources of the Yampa River basin (Hay et al. 2006a; Hay et al. 2006b). The calibrated PRMS model from these studies was used as the starting point in this investigation.

1.3. Modeling methodology

A brief description of the development of climate-change scenarios and model data processing is given here; a detailed description of the methods is given in Hay et al. (Hay et al. 2011). PRMS was calibrated and evaluated for the East and Yampa River basins as part of earlier studies (Hay et al. 1993; McCabe and Hay 1995; Hay et al. 2006a; Hay et al. 2006b; Markstrom et al. 2011). PRMS is a deterministic, distributed-parameter watershed model developed to evaluate the effects of various combinations of precipitation, temperature, and land use on streamflow and general watershed hydrology (Leavesley et al. 1983). PRMS models of the East and Yampa River basins were calibrated using an automated, multiple objective, stepwise approach that applied a shuffled complex evolution global search algorithm (Hay et al. 2006a). This approach ensured that the models produced not only accurate runoff simulation but also realistic estimates of other hydrologic variables (e.g., snow-covered area or snowpack water equivalent).

Given the uncertainty in climate modeling, it is desirable to use more than one GCM to obtain a range of potential future climatic conditions. An analysis of available output from the World Climate Research Programme Coupled Model Intercomparison Project phase 3 (CMIP3) data archive indicated that five GCMs had output for baseline and three future emission scenarios that was suitable for the PRMS models. Monthly precipitation and temperature output from these five GCMs (Table 1) were used to generate ensembles of climate-change scenarios for each basin. These ensembles were simulated with the corresponding PRMS models, and the hydrologic effects and sensitivity of the projections to climate-change scenarios were examined. The GCM output was obtained from the CMIP3 multimodel dataset archive, which is referenced in the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report Special Report on Emission

Table 1. GCM outputs used in this study (Alley et al. 2007). GCM definitions not expanded in the text: Bjerknes Centre for Climate Research Bergen Climate Model (BCC-BCM2.0), Commonwealth Scientific and Industrial Research Organisation Mark version 3.0 (CSIRO Mk3.0), Institute of Numerical Mathematics Coupled Model, version 3.0 (INM-CM3.0), and Model for Interdisciplinary Research on Climate 3.2 (MIROC3.2).

GCM	Source
BCC-BCM2.0	Bjerknes Centre for Climate Research, Norway
CSIRO Mk3.0	Australia Commonwealth Scientific and Industrial Research Organisation, Australia
CSIRO Mk3.5	Australia Commonwealth Scientific and Industrial Research Organisation, Australia
INM-CM3.0	Institute for Numerical Mathematics, Russia
MIROC3.2	National Institute for Environmental Studies, Japan

Scenarios (SRES) (Alley et al. 2007). For each GCM, output from one baseline (historical) and three future carbon emission scenarios were used and are described in Table 2. Because GCM spatial scales are not appropriate for hydrologic modeling, the coarse GCM gridded outputs were statistically downscaled to the climate stations used to calibrate the PRMS models (Hay et al. 2011).

Climate-change fields were derived by calculating the change in climate from baseline to future conditions simulated by each GCM (Figure 2; for more details, see Hay et al. 2011). The 20C3M (baseline) simulation for water years 1988–99 was used to represent baseline climatic conditions. This 12-yr period of record was chosen in part because of the overlap of available historical records from the 14 basins included in a larger study (Hay et al. 2011; Markstrom et al. 2011). The baseline period does not start prior to 1988 because of the lack of Natural Resources Conservation Service Snow Telemetry (SNOTEL) data prior to this date and ends in 1999 because GCM simulations for current conditions end in 1999 for many of the archived models.

Mean monthly climate-change fields (percentage changes in precipitation and degree changes in temperature) were computed for 12-yr moving window periods (from 2001 to 2099) using the baseline simulation for 1988–99 and the A2, B1, and A1B future emission scenarios (Table 2). A 12-yr moving window, starting in 2001 and ending in 2099, results in 1320 future scenarios [(88 of 12-yr climatologies, with one per year starting with 2001–12 and ending with 2088–99) × (3 GCM emission scenarios) × (5 GCMs)].

Climate-change input files for the PRMS projections were generated by modifying the daily PRMS precipitation and temperature inputs (1988–99) with the

Table 2. Climate-change emission scenarios used by GCMs in this study (Alley et al. 2007).

IPCC scenario	Description/assumptions
20C3M (baseline)	Twentieth-century climate used to determine baseline conditions: 1988–99.
B1	Convergent world, with the same global population as scenario A1B but with more rapid changes in economic structures toward a service and information economy: 2001–99.
A1B	Very rapid economic growth, a global population that peaks in midcentury, and rapid introduction of new and more efficient technologies: 2001–99.
A2	Very heterogeneous world with high population growth, slow economic development, and slow technological change: 2001–99

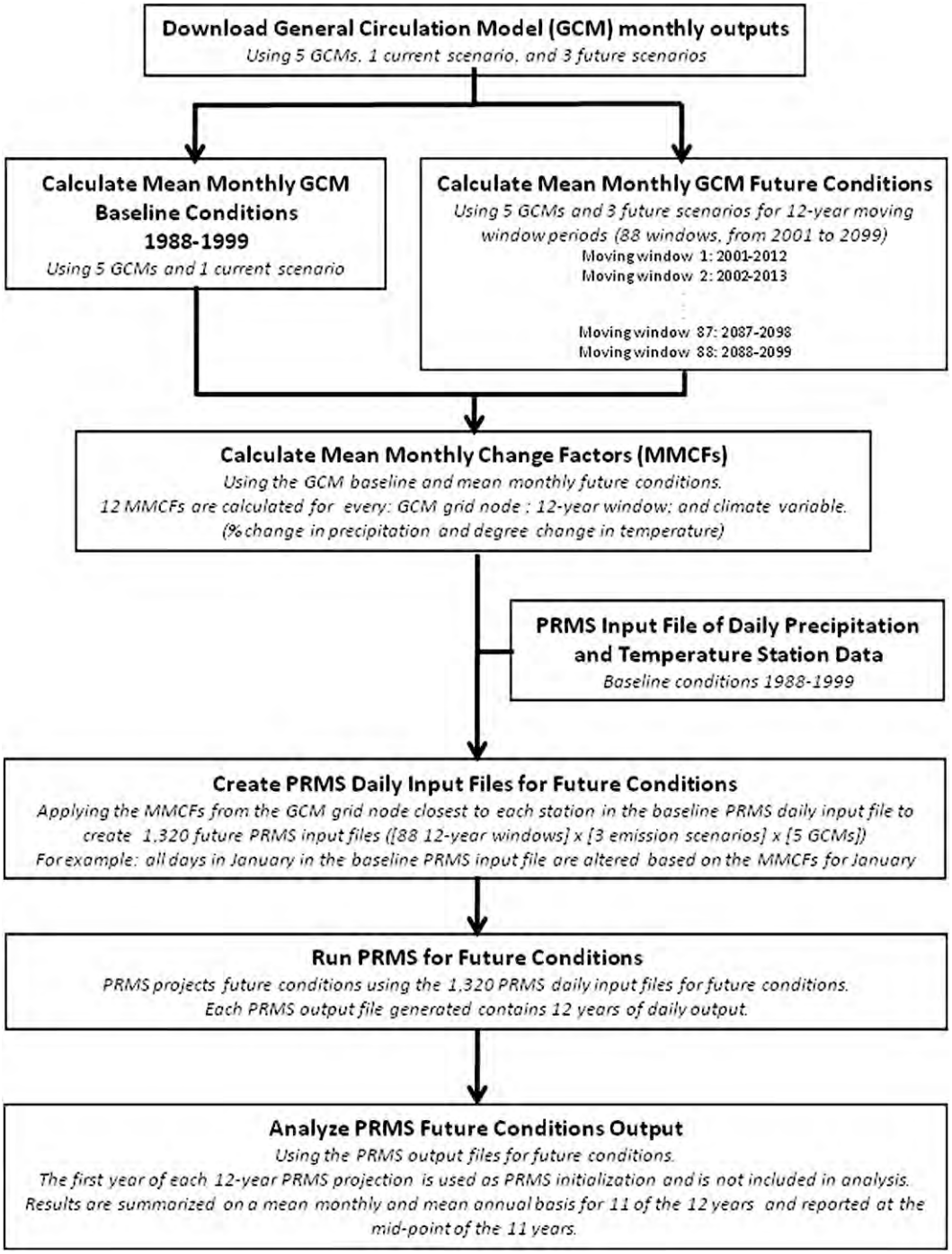

Figure 2. Schematic of the climate-change factor method as applied in this study.

mean monthly climate-change fields derived and downscaled from the GCMs, resulting in 1320 PRMS input files for each study area. The first year of each 12-yr period was used as PRMS initialization and is not included in results analysis. The

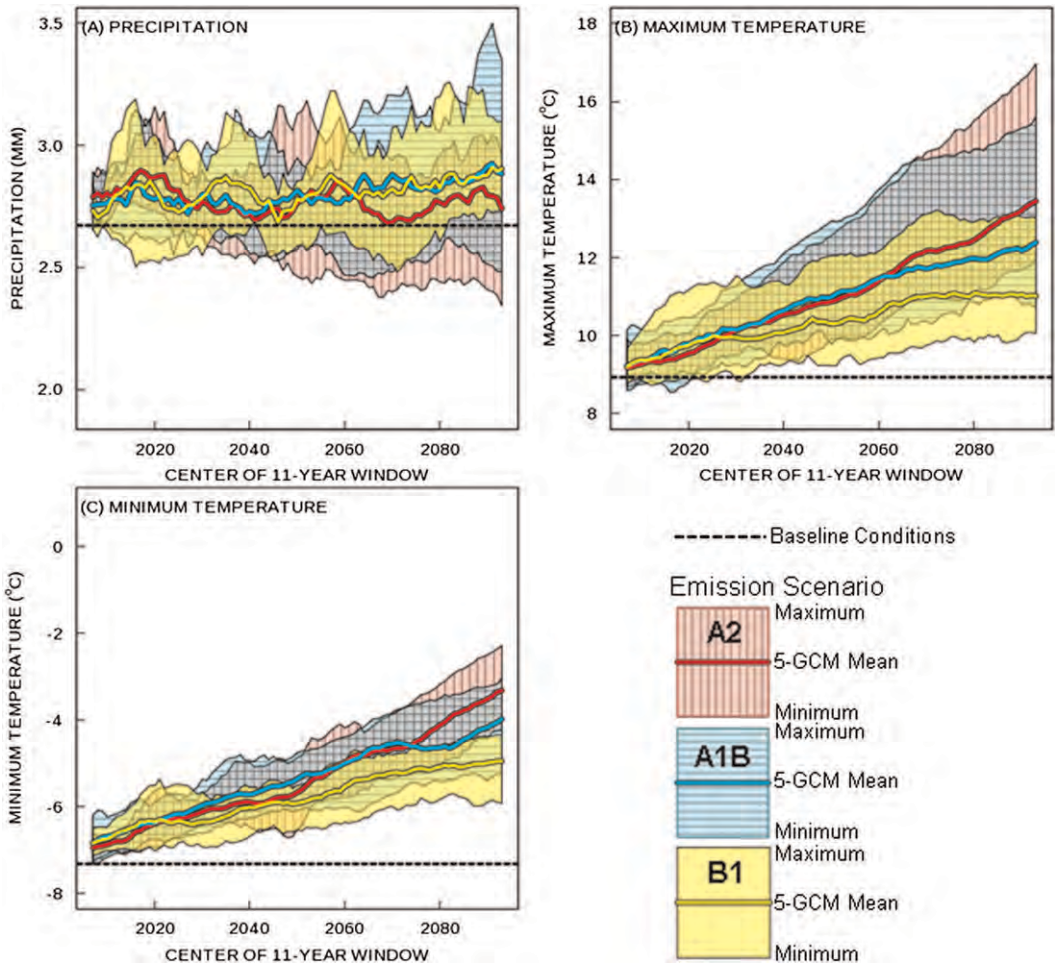

Figure 3. Basin mean daily (a) precipitation, (b) maximum temperature, and (c) minimum temperature for the East River at Almont, Colorado. Baseline conditions (1989–99) are shown as the black dashed line, and the range in future conditions from five GCM simulations are shown for emission scenarios B1 (yellow), A1B (cyan), and A2 (red).

11-yr mean result values for each 12-yr moving window period are plotted at the midpoint of the 11-yr window—hence for 2007–94—in Figures 3–12.

2. Results and discussion

The watershed model simulates spatially distributed estimates of streamflow, components of flow (surface, subsurface, and groundwater), snowpack conditions (i.e., snow-covered area, snowpack water equivalent, and percent of precipitation that falls as snow), and multiple other hydrologic variables of interest. Changes in the development of snowpack and the timing of snowmelt are important in the Yampa and East River basins from a water-supply standpoint and because of potential effects on recreational activities in the area. Graphic and statistical summaries of model

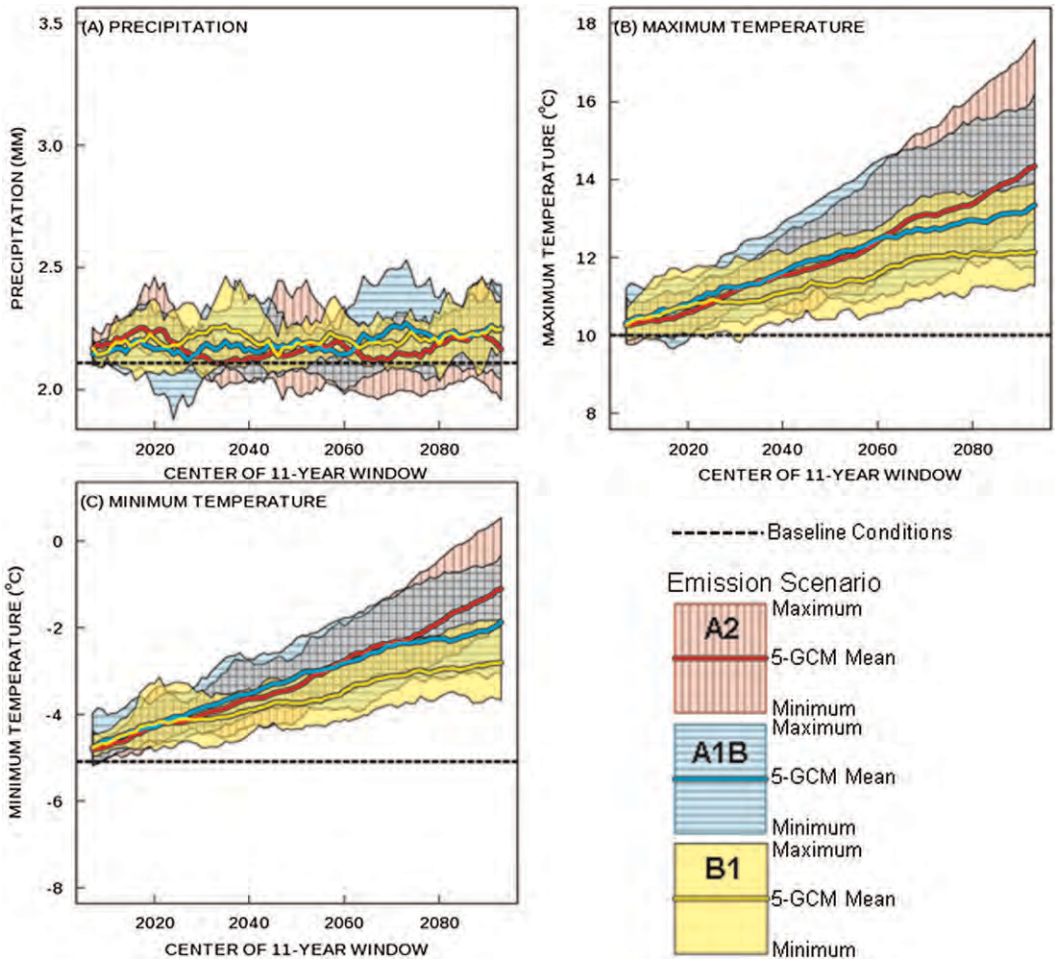

Figure 4. Basin mean daily (a) precipitation, (b) maximum temperature, and (c) minimum temperature for the Yampa River at Steamboat Springs, Colorado. Baseline conditions (1989–99) are shown as the black dashed line, and the range in future conditions from five GCM simulations are shown for emission scenarios B1 (yellow), A1B (cyan), and A2 (red).

inputs (temperature and precipitation) and a variety of model outputs (i.e., streamflow, snow-covered area, and snowpack water equivalent) were evaluated.

2.1. Temperatures and precipitation

Estimates of mean daily precipitation and temperature (maximum and minimum) are shown for the East (Figure 3) and Yampa (Figure 4) River basins. In these figures, baseline conditions (1989–99) are shown with a dashed black line. The three solid colored lines indicate the central tendency (mean) of the 11-yr moving mean values for the five GCM simulations of the three future carbon emission scenarios for 2007–94. The shaded (and hatched) areas show the ranges of potential future climatic conditions simulated by the output from the five GCM simulations for the three future

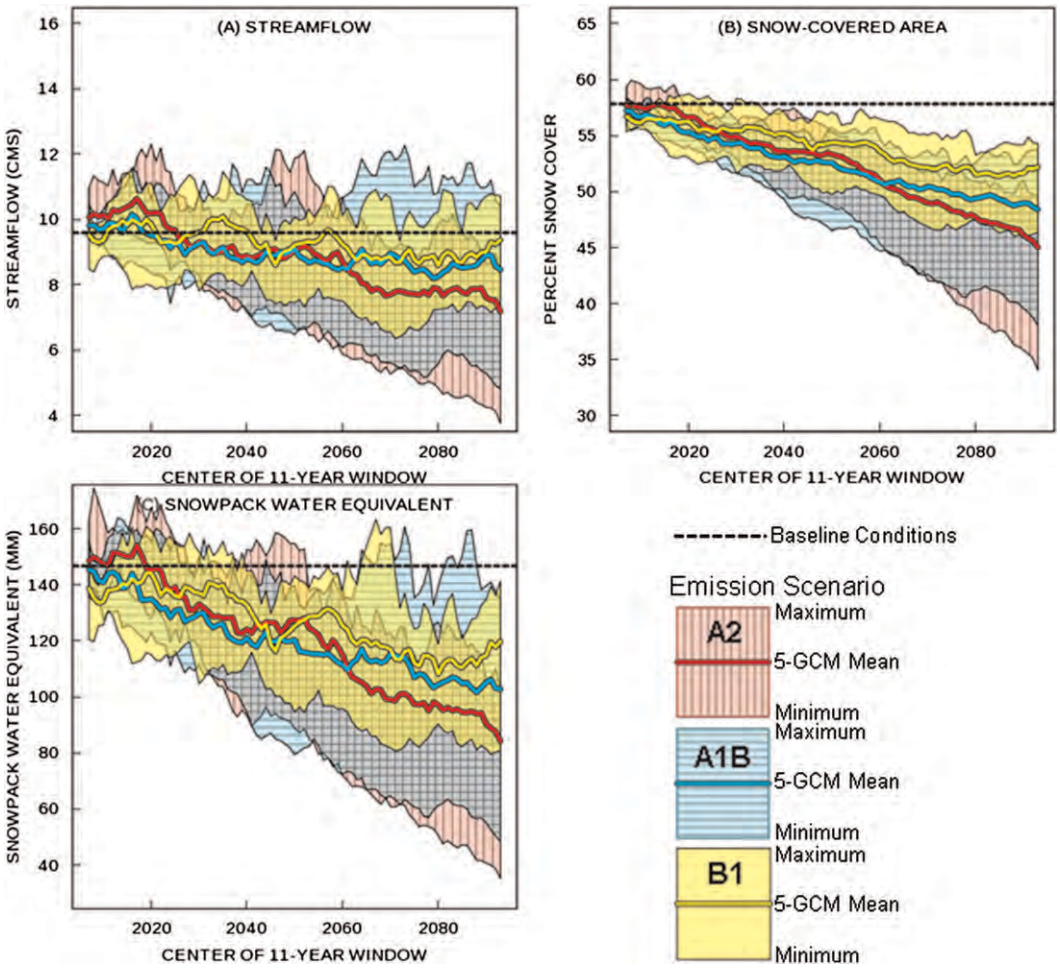

Figure 5. Basin mean daily (a) streamflow, (b) snow-covered area, and (c) snowpack water equivalent for the East River at Almont, Colorado. Baseline conditions (1989–99) are shown as the black dashed line, and the range in future conditions from five GCM simulations are shown for emission scenarios B1 (yellow), A1B (cyan), and A2 (red).

scenarios. Mean daily minimum and maximum air temperatures for both basins indicate a relatively steady increase of up to several degrees Celsius by 2094. Similar increases in minimum and maximum temperature are projected for all three scenarios for the first 20–30 years of the simulation period (Figures 3, 4). After ~2040, the central tendencies for the three scenarios diverge with the smallest projected changes projected for the B1 scenario and the largest projected changes and largest range of projections for the A2 scenario. In both basins, baseline conditions are less than the lowest simulated temperature estimates from all three scenarios after 2040.

A regression analysis is used to identify projected changes in the central tendencies of the five GCMs for each future emission scenarios for selected variables. Regression slopes indicate the annual rate of change for a given variable over the

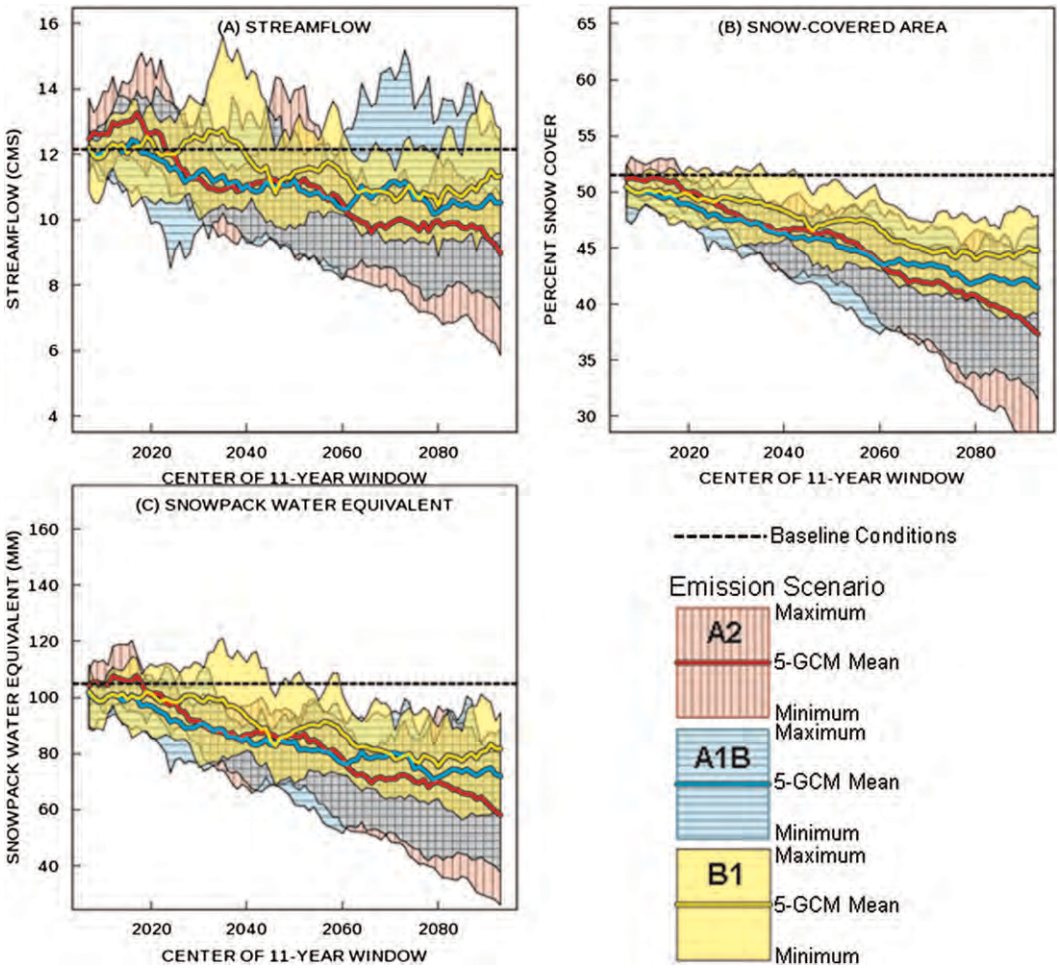

Figure 6. Basin mean daily (a) streamflow, (b) snow-covered area, and (c) snowpack water equivalent for the Yampa River at Steamboat Springs, Colorado. Baseline conditions (1989–99) are shown as the black dashed line, and the range in future conditions from five GCM simulations are shown for emission scenarios B1 (yellow), A1B (cyan), and A2 (red).

simulation period accounting for the effects of lag-1 autocorrelation on the degrees of freedom (Lettenmaier 1976; McCabe and Wolock 1997). In the East and Yampa River basins, there are significant increases to the central tendencies for maximum and minimum temperature projections for all three scenarios, with the B1 scenario projecting the smallest increases and the A2 scenario projecting the largest increases (Tables 3a,b).

In the East and Yampa River basins, the central tendencies for precipitation generally show greater than baseline amounts for all three scenarios, but there are large uncertainties associated with these projections (Figures 3a, 4a). In both basins, baseline conditions are generally within the range of simulations for precipitation estimates from the A1B and A2 scenarios but are occasionally less than the minimum estimates from the B1 scenario. There are small (0.0011 mm yr^{-1} in

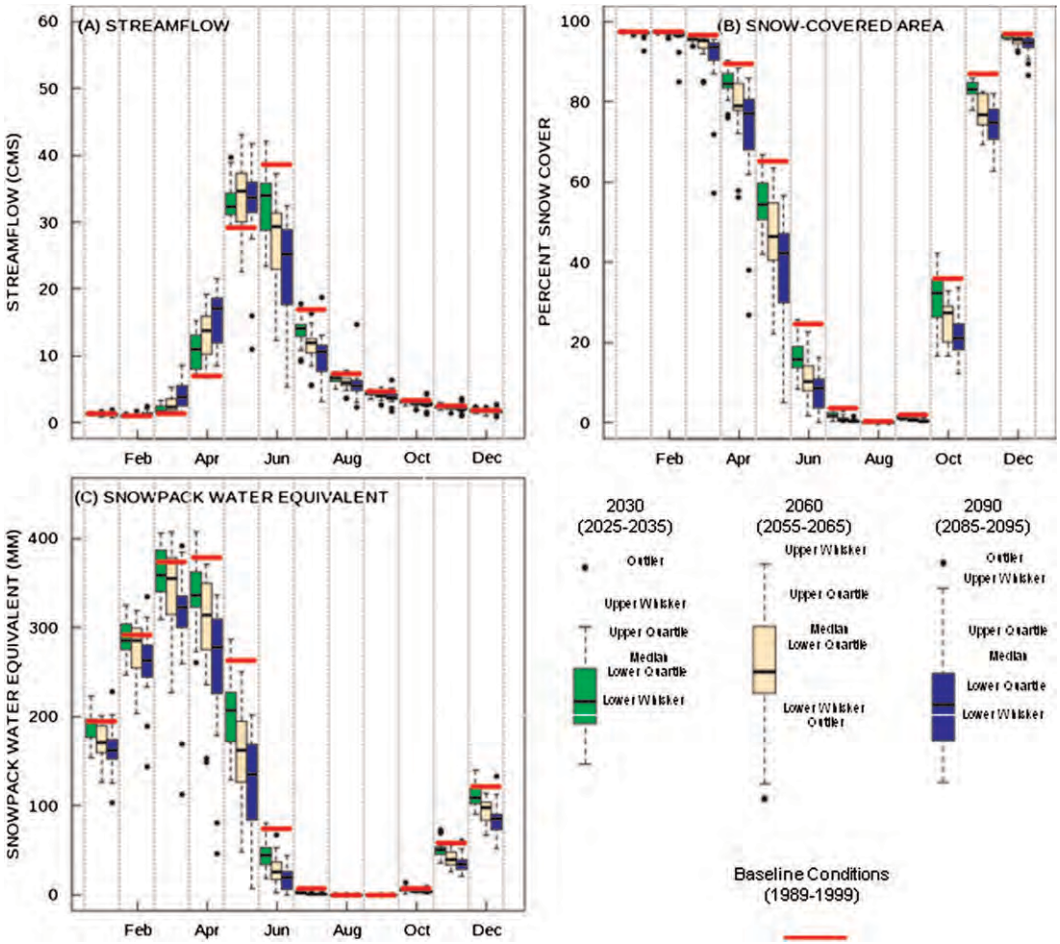

Figure 7. Basin mean daily (a) streamflow, (b) snow-covered area, and (c) snowpack water equivalent by month for the East River at Almont, Colorado. Baseline conditions (1989–99) are shown as the red line, and the range in future conditions from five GCM simulations and three emission scenarios are shown for 2030 (2025–35; green), 2060 (2055–65; tan), and 2090 (2085–95; blue).

Yampa and 0.0013 mm yr^{-1} in East) but significant increases in precipitation for the A1B scenario but no significant increases or decreases for the other two scenarios (Table 3c). This apparent increase but lack of trend in precipitation could be an artifact of the selection of the baseline period for a naturally cyclical variable such as precipitation (Koczot et al. 2011).

2.2. Streamflow

PRMS projections of mean daily streamflow are shown for the East (Figure 5a) and Yampa (Figure 6a) River basins. Mean daily streamflows vary by scenario, but in both basins there are significant decreases to the central tendencies for streamflow

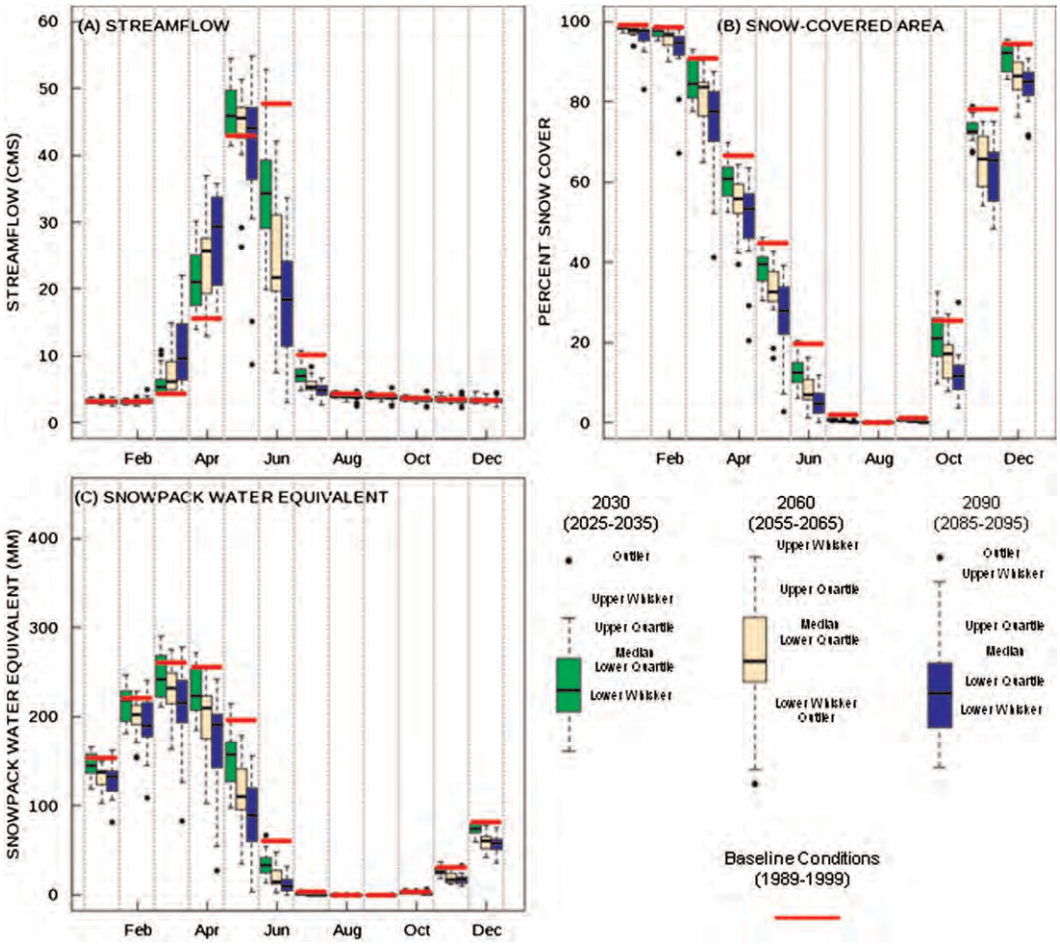

Figure 8. Basin mean daily (a) streamflow, (b) snow-covered area, and (c) snowpack water equivalent by month for the Yampa River at Steamboat Springs, Colorado. Baseline conditions (1989–99) are shown as the red line, and the range in future conditions from five GCM simulations and three emission scenarios are shown for 2030 (2025–35; green), 2060 (2055–65; tan), and 2090 (2085–95; blue).

projections for all three scenarios, with the B1 scenario having the smallest decrease for the East River basin and the A1B scenario having the smallest decrease for the Yampa River basin. The A2 scenario has the largest decreases for both basins (Table 3d). The ranges of these streamflow projections are quite large, especially for the A1B (cyan) and A2 (red) scenarios. For both basins, baseline conditions are almost always within the range of streamflow projections from all three scenarios through 2094. The simulated decreasing tendency for streamflow may be due in part to increases in actual evapotranspiration (ET) that are projected (Table 3e) to occur with increasing temperature; however, other factors such as dust loading (Painter et al. 2010) or limitations in the PRMS models ability to simulate how increasing ET affects streamflow (Hay et al. 2011) also may be important.

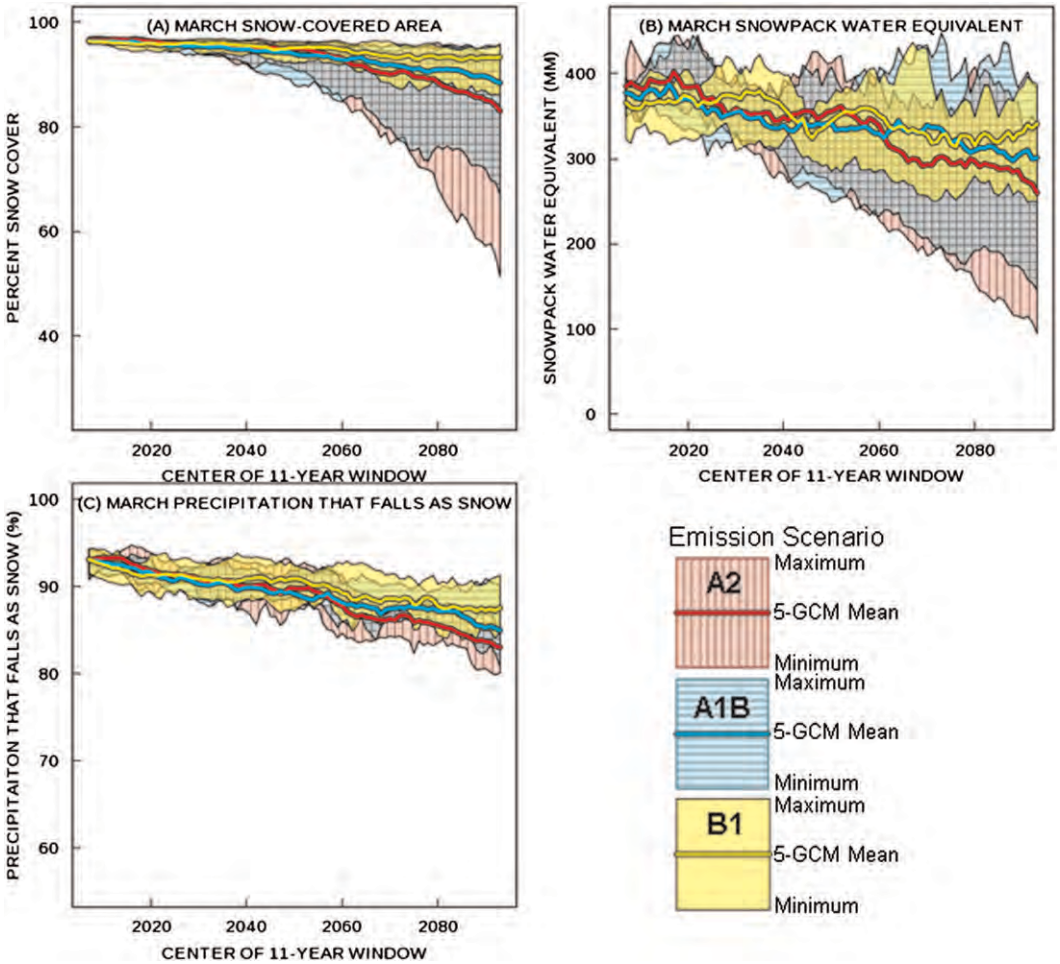

Figure 9. Basin mean daily March (a) snow-covered area, (b) snowpack water equivalent, and (c) precipitation that falls as snow for the East River at Almont, Colorado. The range in future conditions from five GCM simulations is shown for emission scenarios B1 (yellow), A1B (cyan), and A2 (red).

Changes in streamflow can be examined on a monthly basis to determine if the timing of peak runoff is expected to change (Figures 7a, 8a). The solid red lines show PRMS-simulated mean monthly baseline conditions (1989–99) for streamflow, and the box plots represent the range in the mean monthly simulations for the five GCMs and three scenarios for 2030 (green: 2025–35), 2060 (tan: 2055–65), and 2090 (blue: 2085–95). Streamflow in the East River basin (Figure 7a) is projected to increase from March through May, followed by decreases in June through August, with not much change during the fall and winter months (September–February). The results suggest that the timing of peak runoff may shift from June to May by 2060. Streamflow in the Yampa River basin (Figure 8a) is projected to increase from March through May, followed by decreases in June and July, with not much change during the late summer and early winter months (August–February).

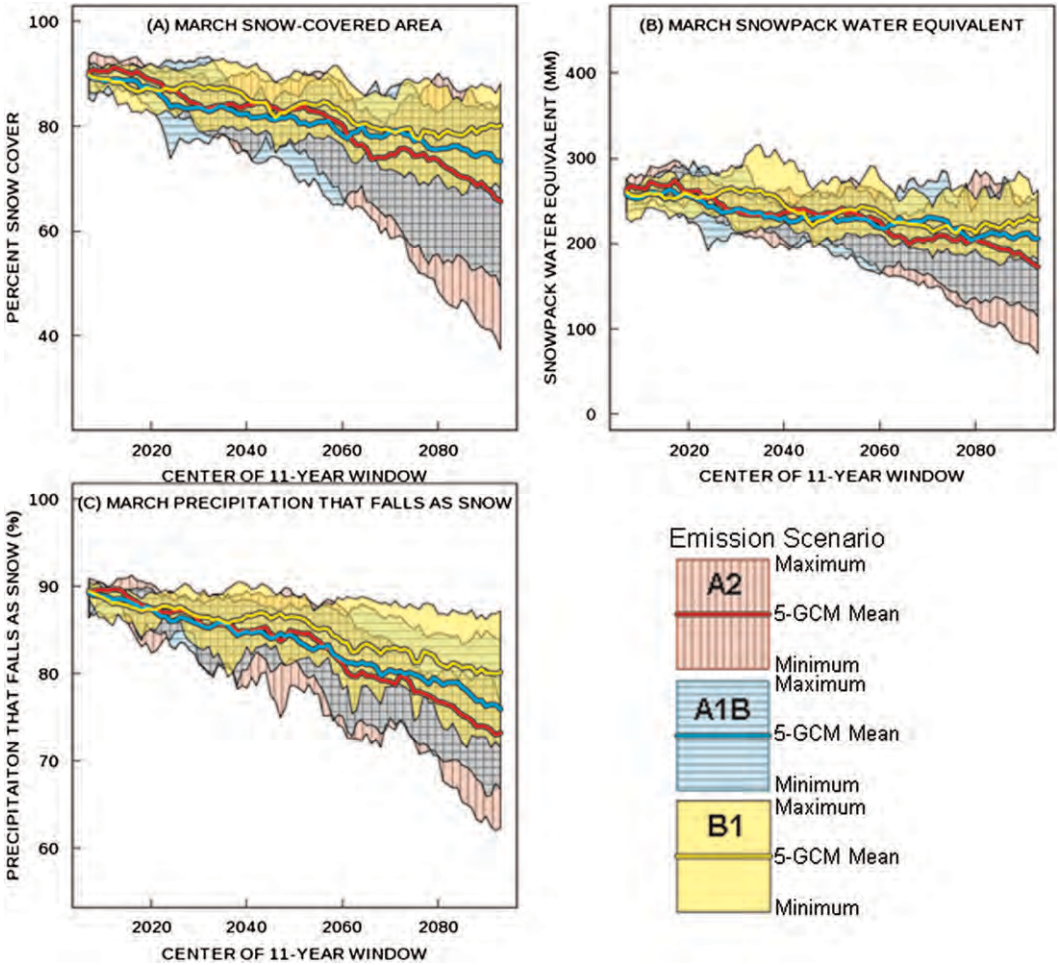

Figure 10. Basin mean daily March (a) snow-covered area, (b) snowpack water equivalent, and (c) precipitation that falls as snow for the Yampa River at Steamboat Springs, Colorado. The range in future conditions from five GCM simulations is shown for emission scenarios B1 (yellow), A1B (cyan), and A2 (red).

By as early as 2030, the timing of peak streamflow is projected to shift from June to May.

2.3. Snow-covered area and snowpack water equivalent

Analysis of other hydrologic variables of interest, output by PRMS, can indicate areas of the water balance most susceptible to changes in climate. Changes in the development of snowpack are important in the East and Yampa River basins from a water-supply standpoint and because of potential effects on recreational activities in the area. Of concern to many stakeholders are winter snow-covered area and snowpack water equivalent. Because of increases in temperature (Figures 3, 4), PRMS projections indicate a steady decrease in mean daily snow-covered area in

both the East and the Yampa River basins (Figures 5b, 6b), with the range increasing with time. In both basins, there are significant decreases to the central tendencies for snow-covered area projections for all three scenarios, with the B1 scenario projecting the smallest decreases and the A2 scenario projecting the largest decreases (Table 3f). By 2050, the maximums of these projections fall below the baseline conditions in both the East and Yampa River basins. A similar steady decrease in mean daily snowpack water equivalent is projected in both the East and the Yampa River basins (Figures 5c, 6c). In both basins, there are significant decreases to the central tendencies for snowpack water equivalent projections for all three scenarios, with the B1 scenario projecting the smallest decreases and the A2 scenario projecting the largest decreases (Table 3g). The implications of these changes for ski areas and other stakeholders in the area depend on when and where the snowpack is being lost, as well as the average annual loss for the basin as a whole.

Changes in snow-covered area and snowpack water equivalent can be examined on a monthly basis to determine when the changes are most significant. Mean monthly snow-covered area in the East River basin (Figure 7b) is projected to decrease in fall (October and November) and spring (April through June). Minimal changes in mean monthly snow-covered area are projected for July through September, when very little of the basin is snow covered under baseline conditions, and for December through March, the coldest winter months. In the Yampa River basin, mean monthly snow-covered area (Figure 8b) is projected to decrease from October through December and from March through June. Minimal changes in mean monthly snow-covered area are projected for July through September and for January and February during the twenty-first century.

Changes in mean monthly snowpack water equivalent follow similar patterns in the two basins. Mean monthly snowpack water equivalent in the East River basin (Figure 7c) is projected to decrease in all months except July through October; however, decreases in January through March are not large until after 2030. Mean monthly snowpack water equivalent in the Yampa River basin (Figure 8c) is projected to decrease in all months except July through October; however, decreases in January and February are not large until after 2030.

In Colorado, the month of March traditionally has the best ski conditions and often the most skier visits (R. Kiklevich 2010, personal communication). Basin mean changes in snow-covered area, snowpack water equivalent, and percent precipitation that falls as snow for March are shown for the East and Yampa River basins in Figures 9 and 10. In both basins, there are similar significant decreases to the central tendencies for snow-covered area and snowpack water equivalent projections for all three scenarios, with the B1 scenario projecting the smallest decreases and the A2 scenario projecting the largest decreases (Tables 3h,i). In the East River basin, the decreases to the central tendencies for March snow-covered area are slightly smaller than those for the year as a whole, and in the Yampa River basin they are slightly larger. Although the decreases to the central tendencies for snow-covered area are similar, the patterns of projected changes are not, especially for the East River basin. Loss of snow-covered area for both basins starts early and is continuous for annual projections (Figures 5b, 6b). Projections for March for the East River basin (Figure 9a) show little change in snow-covered area initially with a wide range of possible outcomes by 2094, whereas projections for March for the Yampa River basin show more linear decreases in snow-covered area (Figure 10a).

2.4. Subbasin-scale results

A distinct advantage of using a distributed-parameter watershed model for identifying the effects of climate change on hydrologic conditions is the ability to project effects at subbasin scales. PRMS divides a basin into a series of hydrologic response units (HRUs) (Figure 1) that are assumed to be homogeneous with respect to hydrologic response to climate inputs (Leavesley et al. 1983). Presumably, ski area locations are picked at least in part because of a tendency to receive snow and keep snowpack relative to the surrounding area. This effect of location within the basin can be examined by comparing projections of snow-covered area, snowpack water equivalent, and precipitation that falls as snow in March for the entire basin with projections from the individual HRUs that represent the ski areas in the model. The boundaries of both ski areas overlap with portions of several model HRUs. Projections of snow-covered area for March for the HRUs that include the base portion and surrounding areas at Crested Butte and Steamboat ski areas show this tendency to catch and keep snow (Figures 11, 12). For the 14.2-km^2 HRU in the East River basin that includes the base of the Crested Butte ski area, the decreases to the central tendencies for March snow-covered area are about the same as those for basin as a whole (Tables 3h,k); however, the patterns of projected changes are slightly different. The loss of snow-covered area until about 2035 is small for basinwide projections (Figure 9a), whereas projections for the HRU show almost no change in March snow-covered area until after 2040. For the 19.3-km^2 HRU in the Yampa River basin that includes the base of the Steamboat ski area, the decreases to the central tendencies for March snow-covered area are slightly smaller than those for the basin as a whole (Tables 3h,k). The loss of snow-covered area starts early and is linear for basinwide projections (Figure 10a), whereas projections for the HRU show little change in March snow-covered area until after 2040 (Figure 12a).

It is recognized that increases in winter temperature can result in less snowfall and earlier snowmelt (Dettinger and Cayan 1995). Basins in which the form of winter precipitation (rain versus snow) is currently sensitive to air temperature are likely to be the most sensitive to future changes in temperature (Stewart 2009). Both the East and Yampa River basins appear to be at high enough elevation and are cold enough to be somewhat protected from projected increases in temperature and the resulting effect on snow-covered area until after 2040.

In both the East and Yampa Rivers basins, decreases to the central tendencies for March snowpack water equivalent are larger for the HRUs than for the basins as a whole (Tables 3i,l). This suggests that in both basins there are areas that will have less loss of March snowpack water equivalent than the selected HRUs. In the East River basin, the March snowpack water equivalent for the selected HRU is initially smaller than the March snowpack water equivalent for the whole basin (Figures 9, 11), whereas the opposite is true for the selected HRU in the Yampa River basin (Figures 10, 12). PRMS projections indicate a steady decrease in the percentage of March precipitation that falls as snow in both basins (Figures 9c, 10c) with similar changes projected for the two HRUs that fall within those basins (Figures 11c, 12c). There are significant decreases to the central tendencies for March precipitation that falls as snow projections for all three scenarios, with the B1 scenario projecting the smallest decreases and the A2 scenario projecting the largest decreases (Tables 3j,m) in both basins and HRUs.

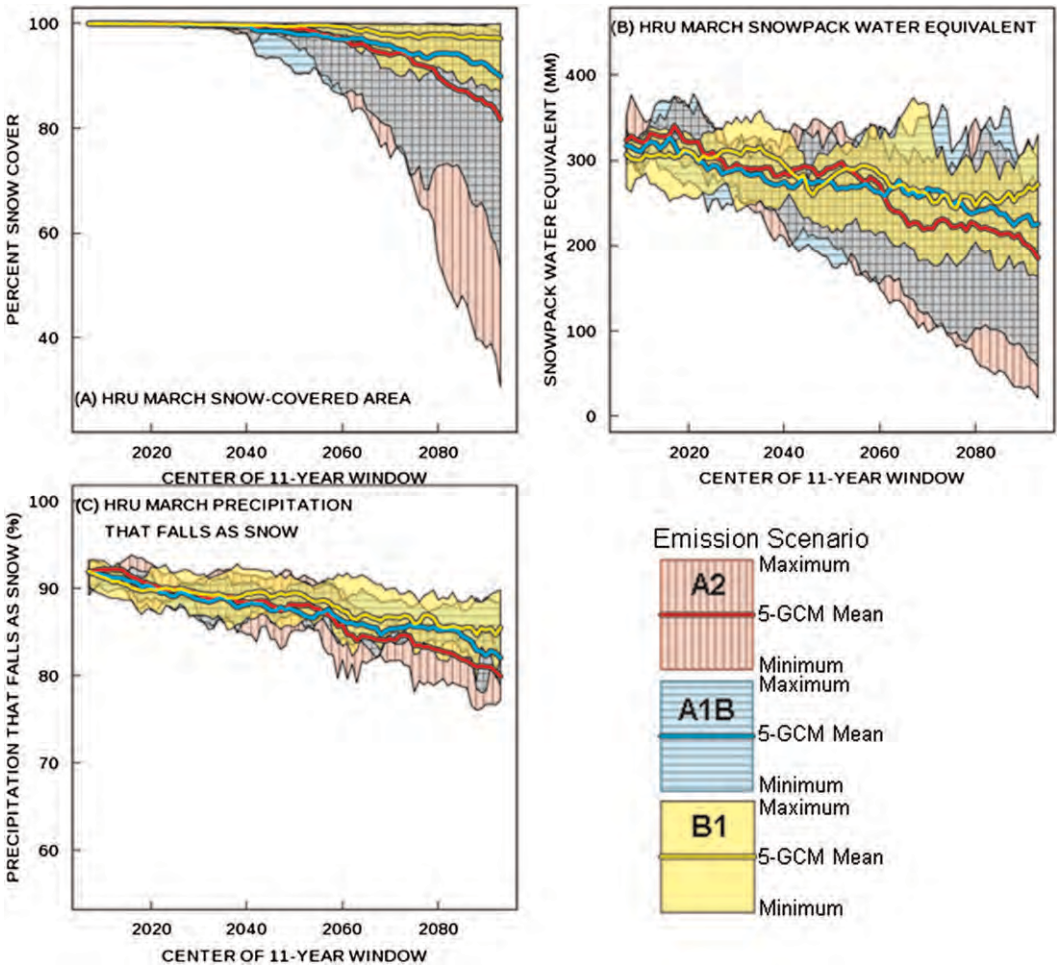

Figure 11. Mean daily March (a) snow-covered area, (b) snowpack water equivalent, and (c) precipitation that falls as snow for the HRU in the East River basin that includes the base portion of Crested Butte ski area, Colorado. The range in future conditions from five GCM simulations is shown for scenarios B1 (yellow), A1B (cyan), and A2 (red).

3. Discussion and conclusions

This research demonstrates the utility of a distributed-parameter watershed models for projecting the potential effects of climate change at basin and subbasin scales. We used ski areas as examples of subbasin scale, but this type of analysis can be done for any local area and hence is important to water suppliers and other stakeholders. Water users in Colorado (and surrounding states) are concerned about decreases in snowpack and changes in the amount or timing of snowmelt, runoff, and streamflow. Ski areas and other stakeholders have additional concerns about changes in snow-covered area and the amount of precipitation that falls as snow during winter months. Streamflow in the East and Yampa River basins is under increasing demand from water users and recreationalists both within and outside

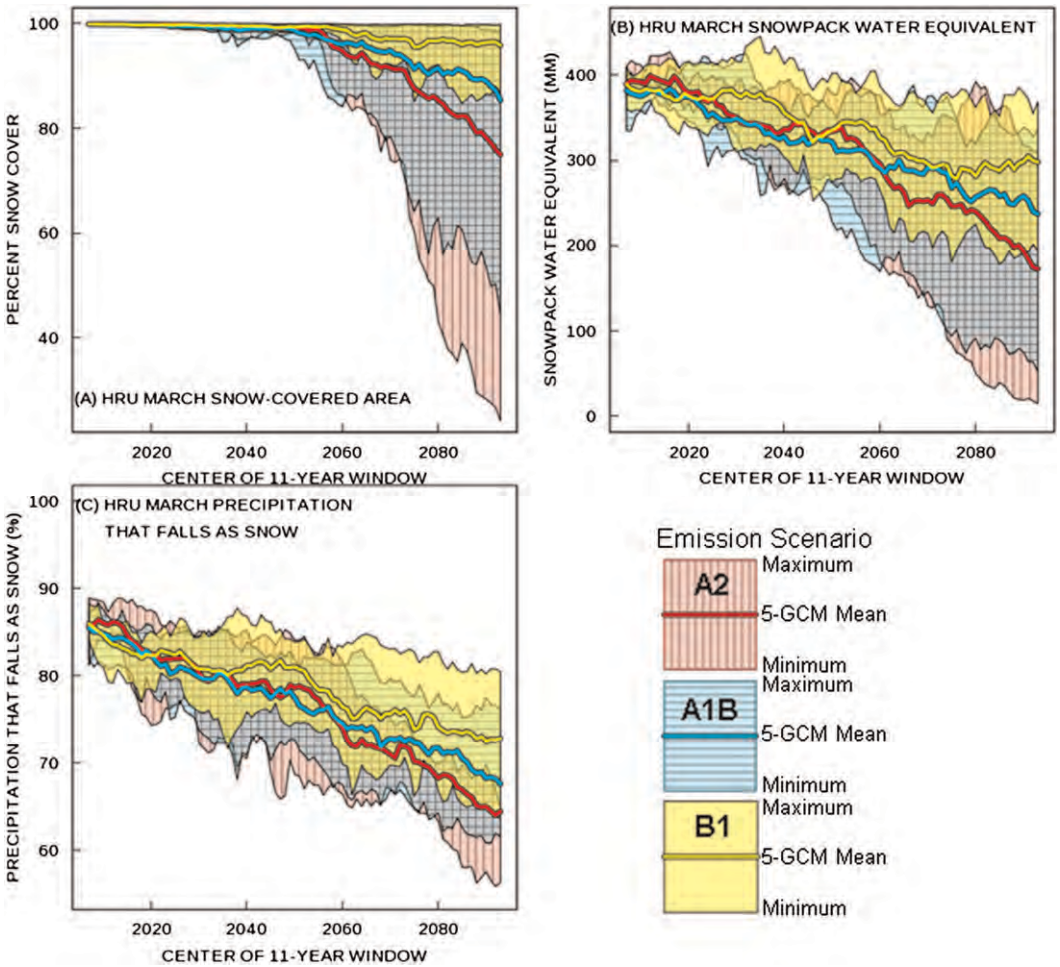

Figure 12. Mean daily March (a) snow-covered area, (b) snowpack water equivalent, and (c) precipitation that falls as snow for the HRU in the Yampa River basin that includes the base portion of the Steamboat ski area, Colorado. The range in future conditions from five GCM simulations is shown for emission scenarios B1 (yellow), A1B (cyan), and A2 (red).

those basins. Potential changes in streamflow resulting from future changes in climate may add to the stress that these basins will experience as a result of projected increases in domestic and industrial water use. Projected changes in future climate in the East and Yampa River basins likely will affect both the quantity and timing of streamflow and have the potential to change snowpack conditions that support recreational activities such as skiing. Results from this modeling effort show that there is a wide range of possible outcomes for future snowpack conditions in Colorado. The results also highlight the importance of understanding the differences between projections for entire basins and projections for particular locations within those basins.

Projected increases in temperature (and the resulting projected increase in actual evapotranspiration) coupled with small projected changes in precipitation result in

Table 3. Projected change by year (slope) of the central tendencies of the five GCMs for three future emission scenarios for the East and Yampa River basins. (Bold numbers indicate significant trends at $p < 0.05$.)

Basin	Slope, scenario B1	Slope, scenario A1B	Slope, scenario A2
(a) Basin area-weighted maximum temperature (°C)			
East	**0.022**	**0.037**	**0.049**
Yampa	**0.023**	**0.035**	**0.047**
(b) Basin area-weighted minimum temperature (°C)			
East	**0.022**	**0.031**	**0.040**
Yampa	**0.022**	**0.033**	**0.042**
(c) Basin area-weighted precipitation (mm)			
East	0.0011	**0.0013**	−0.0007
Yampa	0.0004	**0.0011**	−0.0001
(d) Streamflow from basin ($m^3\ s^{-1}$)			
East	**−0.0118**	**−0.0150**	**−0.0347**
Yampa	**−0.0211**	**−0.0205**	**−0.0415**
(e) Actual evapotranspiration for basin (mm)			
East	**0.0025**	**0.0031**	**0.0034**
Yampa	**0.0017**	**0.0024**	**0.0026**
(f) Snow-covered area for basin (%)			
East	**−0.07**	**−0.10**	**−0.15**
Yampa	**−0.08**	**−0.10**	**−0.16**
(g) Snowpack water equivalent for basin (mm)			
East	**−0.38**	**−0.47**	**−0.77**
Yampa	**−0.32**	**−0.34**	**−0.54**
(h) March snow-covered area for basin (%)			
East	**−0.04**	**−0.09**	**−0.14**
Yampa	**−0.14**	**−0.17**	**−0.27**
(i) March snowpack water equivalent for basin (mm)			
East	**−0.63**	**−0.83**	**−1.42**
Yampa	**−0.57**	**−0.59**	**−0.99**
(j) March precipitation that falls as snow for basin (%)			
East	**−0.116**	**−0.155**	**−0.217**
Yampa	**−0.151**	**−0.194**	**−0.260**
(k) March snow-covered area for HRU (%)			
East	**−0.04**	**−0.10**	**−0.16**
Yampa	**−0.05**	**−0.14**	**−0.25**
(l) March snowpack water equivalent for HRU (mm)			
East	**−0.75**	**−0.99**	**−1.61**
Yampa	**−1.35**	**−1.66**	**−2.50**
(m) March precipitation that falls as snow for HRU (%)			
East	**−0.126**	**−0.168**	**−0.238**
Yampa	**−0.144**	**−0.191**	**−0.248**

projected decreases in streamflow, snow-covered area, and snowpack water equivalent and earlier peak runoff in both the East and Yampa River basin by the end of the twenty-first century. Decreasing snowpack in the East and Yampa River basins would be important because of potential adverse effects on water supply and recreational activities. PRMS projections of the three future scenarios indicate a central tendency for decreases in basin mean snow-covered area and snowpack water equivalent, with the range of the projected decreases increasing with time. When examined on a monthly basis, the projected decreases are most dramatic during fall and spring. When examined for the month of March, the decreases in snow-covered area for the

entire basin start earlier and are more linear than are projections for the HRUs that include the ski areas in the PRMS models. These projections indicate only very small changes in March snow-covered area at both ski areas for the three future scenarios until ~2040. These portions of the basins appear to be at high enough elevation and are cold enough to be protected from projected increases in temperature and the resulting effect on snow-covered area until after 2040. The rates of decrease for snowpack water equivalent and precipitation that falls as snow are similar at the basin and subbasin scale in both the East and Yampa River basins. These results suggest that for the near future (through the first half of the twenty-first century) those stakeholders who rely on snowpack in the East and Yampa River basins may not experience the "best of times" but maybe not "the winter of despair" either.

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