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The Relationships between Climatic and Hydrological Changes in the Upper Mississippi River Basin: A SWAT and Multi-GCM Study

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ABSTRACT

Changes in major climatic and hydrological quantities in the upper Mississippi River basin and their interrelationships are studied with the Soil and Water Assessment Tool being driven by the contemporary climate and future scenario simulations of 10 global models in the Intergovernmental Panel on Climate Change (IPCC) Data Archive. Although the seasonal cycles of climate and hydrological quantities simulated by the 10 models have differences, the ensemble is very close to the observation. Ensemble predictions show that with warming in all months, precipitation decreases in summer but increases in all other seasons. Correspondingly, streamflow decreases in all seasons except winter, evapotranspiration decreases in July–September and increases in all other months, and snowmelt increases in winter but decreases in spring and fall. To understand the linkages between the cross-century changes of climate and hydrological quantities and the relative importance of the changes of temperature and precipitation to the changes of hydrological quantities, relationships between interannual variations of these quantities are investigated. It is shown that the change rates of the hydrological quantities with respect to temperature and precipitation obtained from regressions of interannual variations can vary greatly from month to month; however, on a monthly basis, they do not change much from the current to the future periods. Evaluations with these change rates indicate that for interannual variations of hydrological quantities, both variations of temperature and precipitation are important, and their relative importance depends on the month of the year. However, the changes of hydrological quantities from the means of the current years to the means of the future are dominated by warming in all months, and the influence from change of precipitation is much smaller. The changes of the hydrological quantities can be well predicted with the change rates from the warming alone.

1. Introduction

Hydrological impact assessments of warming due to anthropologically increased greenhouse gases are very important for the management of water resources and for plans for agriculture and other uses of water. Relationships between changes of the hydrological cycle and the change of climate have been studied by many researchers (e.g., Risbey and Entekhabi 1996; Walter et al. 2004; Groisman et al. 2004; Hamlet et al. 2005; Qian et al. 2007; Miller and Piechota 2008). Risbey and Entekhabi (1996) studied observations of the Sacramento basin annual mean streamflow response to precipitation and temperature, and they showed that streamflow amounts in the basin are strongly sensitive to precipitation but insensitive to mean seasonal temperature. Walter et al. (2004) and Groisman et al. (2004) found from observations that temperature, precipitation, streamflow, and evapotranspiration all have increased during the past 50 years over the contiguous United States. Qian et al. (2007) analyzed the hydroclimatic trends in the Mississippi River basin from 1948 to 2004, and they revealed that, with the increase...
of precipitation, both runoff and evapotranspiration have increased. The increase of evapotranspiration is shown from a model to be dominated by the change of precipitation, whereas the change of temperature has a small effect. Miller and Piechota (2008) examined changes of temperature, precipitation, and streamflow in the Colorado River basin using National Climatic Data Center (NCDC) climate data and gauge-observed streamflow data, and they pointed out that streamflow has increased between November and February but decreased during the traditional peak runoff season of April–July, which corresponds to the persistent increases of temperature throughout the year. Precipitation has notably increased over only some of the climate divisions during February, but it remained relatively unchanged otherwise.

Hydrological cycle–climate relationships can be affected by land use change or other human activities. Lettenmaier et al. (1994) evaluated changes of streamflow relative to changes of temperature and precipitation from 1948 to 1988 over the continental United States, and they found that observed changes of streamflow are not entirely consistent with changes of climatic variables and may be due to a combination of climatic and water management effects. Adam and Lettenmaier (2008) studied trends of temperature, precipitation, and streamflow in northern Eurasia from 1936 to 2000 to understand the extent to which the change of river discharge can be attributed to climate change. They found that changes in reservoir operation have influenced streamflow seasonality, whereas warming and increased precipitation can affect streamflow and other hydrological quantities. The dependence of relationships between changes of the hydrological cycle and climate on local factors such as land surface and soil characteristics as well as management conditions leads to different relationships from one river basin to another.

The river basin we examine in this study is the upper Mississippi River basin (UMRB), which has a drainage area of 447,500 km². The large interannual variability of climate in the UMRB, such as the 1988 drought and the 1993 flood, can create very large effects on agriculture. A better understanding of how the hydrological conditions of the UMRB will vary with changes in climate will improve agricultural decision making. Assessments of local and regional effects of changes of the hydrological cycle with climate identify the need for improved capabilities for modeling the hydrological cycle and its individual components at the subwatershed level. The publication of the Fourth Assessment Report (AR4) by the Intergovernmental Panel on Climate Change (IPCC; Solomon et al. 2007) has brought increased attention to climate change at regional scales. Although extensive simulations of climate change by regional climate models have not been reported yet, the AR4 offers more interpretation of global climate model results at regional scales than previous reports.

Jha et al. (2004) showed that for the UMRB, the Soil and Water Assessment Tool (SWAT) watershed model (Arnold and Fohrer 2005) provided good results for simulating annual streamflow. However, it is not clear whether spatial refinement of global model results is warranted for simulating streamflow for this watershed. Use of data from global climate models directly is an alternative to using regional climate models or statistical models to downscale global results. By comparing observations of streamflow at Grafton, Illinois, with simulated results, Takle et al. (2005) found that although no individual low-resolution global model was able to give a distribution of annual flows that was not statistically different from the mean of observed values, the ensemble of nine models did produce a credible distribution that was statistically significant.

In the present study, the contemporary (current) and future Special Report on Emissions Scenarios (SRES; A1B) climates from 10 global models in the IPCC AR4 are used to drive SWAT for the UMRB to simulate changes of the major components of the hydrological cycle, including streamflow, evapotranspiration, and snowmelt. As revealed from previous studies, the changes of these hydrological quantities are caused by changes in both temperature and precipitation, along with some other meteorological and local parameters. While presenting the changes of the hydrological quantities from the current to the future periods, we also attempt to understand the effects of changes of temperature and precipitation on the changes of hydrological quantities. Questions we address include the following: which variable plays the dominant role? do the effects vary with time of year? and do seasonal patterns of the effects vary between current and future climates? Similar questions are asked for the interannual variations, which include whether variations of temperature and precipitation positively and equally contribute to the interannual variations of the hydrological quantities. Understanding these issues will enable for better assessment and prediction of the hydrological effects of climate change.

The 10 global climate models and the SWAT model are introduced in section 2. Results of current climate from climate models and hydrological cycle from SWAT are presented in section 3. The relationships between the year-to-year variations of hydrological and climate quantities, and the relative importance of the contributions from temperature and precipitation are analyzed in section 4. In section 5, we focus on the cross-century changes of hydrological quantities and understanding their linkages to the warming climate. Summary and discussions are provided in section 6.
2. Models, data, and procedures

a. Global climate models

Meteorological data input to SWAT includes daily values of maximum and minimum temperature, total precipitation, mean wind speed, total solar radiation, and mean relative humidity. In the current IPCC Data Archive (available online at http://www-pcmdi.llnl.gov/), 10 climate models (including the two versions of models from the Geophysical Fluid Dynamics Laboratory; Table 1) provide daily values of these quantities. Data from the 10 models for both the twentieth-century contemporary climate (20C3M) for the period 1961–2000 and the twenty-first century A1B emission scenario (Houghton et al. 2001) for the period 2046–65 are used in this study for SWAT simulations (Table 2).

b. SWAT model

The SWAT version 2005 (Arnold and Fohrer 2005), a watershed-scale hydrological model, was used in this study to simulate the hydrological cycle. The UMRB is divided into 131 subwatersheds (Fig. 1), which is consistent with U.S. Geological Survey 8-digit Hydrologic Cataloging Unit watershed boundaries, as described by Seaber et al. (1987). Each of these subwatersheds is subdivided into Hydrological Response Units (HRUs), creating a total of nearly 2800 HRUs. The climate data used for each subwatershed are taken from the GCM grid point that is the closest to the centroid of the subwatershed, and the selection is made automatically by the ArcView interface of SWAT (AVSWAT). The role of subsurface tile drainage is considered. Details of land use, soils, and topography data for the UMRB are described by Gassman et al. (2006).

c. Observed data

Monthly streamflow measurements at U.S. Geological Survey gauge station 05587450, the watershed outlet near Grafton, Illinois, for the period of 1989–97 are used to calibrate and validate SWAT by adjusting several model parameters and comparing simulated streamflow with measured values (Jha et al. 2006). Annual totals of simulated and measured streamflow have a strong correlation. The coefficient of determination and Nash–Sutcliffe’s efficiency are 0.94 and 0.91, respectively, during the calibration period (1981–92) and 0.95 and 0.95, respectively, during the validation period (1993–2003). Observed daily precipitation, maximum temperature, and minimum temperature in the period of 1979–2004 from weather stations in the UMRB (Table 2), available at the National Climatic Data Center (available online at http://www.ncdc.noaa.gov/oa/ncdc.html), are used to calculate the daily input data for each subwatershed with spatial average. When simulating streamflow by SWAT with these observed data, other input variables (including relative humidity, solar radiation, and wind speed) are generated by the weather generator of SWAT, and they are used in the SWAT simulations for the current and future scenario climate. The simulated streamflow is compared with the measured streamflow.

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### Table 1. Global climate models used in the SWAT simulations.

<table>
<thead>
<tr>
<th>Model ID</th>
<th>Institution</th>
<th>Model name</th>
<th>Lon × lat resolution (°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>M01</td>
<td>Bjerknes Centre for Climate Research (Norway)</td>
<td>BCCR_BCM2.0</td>
<td>2.8 × 2.8</td>
</tr>
<tr>
<td>M02</td>
<td>Canadian Centre for Climate Modelling and Analysis</td>
<td>CCCMA_CGCM3.1</td>
<td>3.8 × 3.7</td>
</tr>
<tr>
<td>M03</td>
<td>Météo-France/Centre National de Recherches Météorologiques (France)</td>
<td>CNRM_CM3</td>
<td>2.8 × 2.8</td>
</tr>
<tr>
<td>M04</td>
<td>Commonwealth Scientific and Industrial Research Organisation (CSIRO) (Australia)</td>
<td>CSIRO_MK3.0</td>
<td>2.8 × 2.8</td>
</tr>
<tr>
<td>M05</td>
<td>National Oceanic and Atmospheric Administration (NOAA) Geophysical Fluid Dynamics Laboratory (USA)</td>
<td>GFDL_CM2.0</td>
<td>2.5 × 2.0</td>
</tr>
<tr>
<td>M06</td>
<td>NOAA Geophysical Fluid Dynamics Laboratory (USA)</td>
<td>GFDL_CM2.1</td>
<td>2.5 × 2.0</td>
</tr>
<tr>
<td>M07</td>
<td>Center for Climate System Research (Japan)</td>
<td>MIROC3.2_MEDRES</td>
<td>2.8 × 2.8</td>
</tr>
<tr>
<td>M08</td>
<td>Meteorological Institute of the University of Bonn (Germany)</td>
<td>MIUB_ECHO_G</td>
<td>3.8 × 3.7</td>
</tr>
<tr>
<td>M09</td>
<td>Max Planck Institute for Meteorology (Germany)</td>
<td>MPI_ECHAM5</td>
<td>1.9 × 1.9</td>
</tr>
<tr>
<td>M10</td>
<td>Meteorological Research Institute (Japan)</td>
<td>MRI_CGCM2.3.2A</td>
<td>2.8 × 2.8</td>
</tr>
</tbody>
</table>

### Table 2. SWAT simulations, their driving climates, and years simulated and analyzed.

<table>
<thead>
<tr>
<th>SWAT-simulated hydrological cycle (SF, ET, and SM)</th>
<th>Driving climate ((T_{\text{max}}, T_{\text{min}}, \text{and } P))</th>
<th>Years simulated and analyzed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Future</td>
<td>Future scenario (A1B) climate of 10 GCMs in IPCC AR4</td>
<td>2046–65 (2048–65)</td>
</tr>
</tbody>
</table>
4. Analysis procedures

The output of the first two years from SWAT is not used for analysis as a result of the spinup of the model (Table 2). The current climate and hydrological quantities from the 10 climate models and SWAT used for analysis include the 38 years from 1963 to 2000, and the future climate and hydrological quantities include the 18 years from 2048 to 2065. The observed climate data and the hydrological quantities based on the observed climate data used for analysis include the 24 years from 1981 to 2004. The input climate and the simulated hydrological quantities are all first averaged over the UMRB, with the area of each watershed being taken into account. Statistical analyses such as averages, standard deviations, correlations, regressions, and significance tests are then made with these spatially averaged quantities for each model. These statistical quantities are finally averaged over the 10 models to produce the ensemble mean quantities.

3. Seasonal variations of climate and hydrological cycle

Temperature and precipitation—the most important input climate variables for SWAT—are the focus of analysis in this study. Because the relationships of the minimum temperature with hydrological quantities follow well the relationships of the maximum temperature, the figures of minimum temperature are not presented.

Figure 2 shows the current 38-yr mean seasonal cycles of the input climate and output hydrological quantities averaged over the UMRB for all climate models as well as their ensemble means. Also plotted are the 24-yr averages of the observed climate quantities and the “observed” hydrological quantities that are actually the SWAT-simulated hydrological quantities, with the observed climate being the input. Seasonal cycles of simulated temperature, especially their ensemble, are in agreement with the observed. Relative to the range of its seasonal variation, temperature has a small intermodel variation (Fig. 2a).

Precipitation (P) has its maximum in late spring–early summer and minimum in winter. Compared with temperature, the intermodel variation of precipitation relative to the seasonal range is much larger (Fig. 2b). The seasonal cycle of the precipitation ensemble is in general agreement with the observed, although the annual extreme may be a month or two off for some models. Because the focus of this study is changes of climate and hydrological quantities, rather than these quantities themselves, the biases of model output are not treated.

Streamflow (SF), following precipitation, also has a maximum in late spring–early summer and a minimum in winter. The intermodel variation of streamflow is much larger than that of precipitation, such that the streamflow in late spring–early summer of one model can even be much smaller than that in winter of another model. However, even though the seasonal cycles of the streamflow projected by the 10 models have large variability, their ensemble is very close to that simulated by SWAT from the observed climate (Fig. 2c). These streamflow results from SWAT are close, especially in seasonal patterns, to the streamflow of the North American Regional Reanalysis (NARR) averaged over the same period (1981–2004).

The seasonal variation of ensemble evapotranspiration (ET) follows well that of temperature, and the intermodel variation is small relative to its seasonal variation (Fig. 2d). Similar to streamflow, snowmelt (SM) shows quite large intermodel variation (Fig. 2e). The ensembles of evapotranspiration and snowmelt are very close to that simulated by SWAT from the observed climate. These SWAT-simulated evapotranspiration and snowmelt are also very close to that from the NARR (Figs. 2d–2e).

4. Relationships between interannual variations of climate and hydrological cycle

Temperature and precipitation are independent quantities when input to SWAT, although they may be linked through atmospheric processes. In the hydrological model, climate is the external forcing of the hydrological cycle, and there is no interaction between them. The daily hydrological quantities in the model respond mainly to the
climate quantities of the same day. The purpose of this section is to investigate the relationships between the interannual variations of the monthly averaged climate and hydrological quantities of the same month.

Figure 3 provides the 10-model-averaged correlation coefficients $R$ between the monthly hydrological and climate quantities of each month in the current and future periods. Overall, with the warming from the current to the future periods, the seasonal patterns of the correlations of hydrological quantities with temperature and precipitation do not change much. Streamflow has negative correlation with temperature in all seasons except winter (Fig. 3a), and the correlation is significant at the 0.05 level with two-tailed $t$ tests in summer of both the current and future periods. It has positive correlation with precipitation in all seasons (Fig. 3b).

The positive relation between streamflow and precipitation is easy to understand from the soil water balance. Groisman et al. (2001) found a significant relationship in the eastern United States between the frequency of heavy precipitation and high-streamflow events, both annually and during the months of maximum streamflow. How can we understand the linkage of the interannual streamflow with temperature? Streamflow can be regulated by the change of soil water, which links to evapotranspiration and snowmelt—both of which are related to temperature. Thus streamflow can be affected by temperature. The negative correlation of streamflow with temperature in the warm months may be a reflection of the positive correlation between streamflow and precipitation because precipitation and temperature in the UMRB are strongly negatively correlated in the
warm months (figure not shown), which is consistent with the result of Trenberth and Shea (2005). In winter, although future temperature increases, it is still low and precipitation can still totally be in the form of snow; however, for the same amount of precipitation, the higher temperature increases snowmelt, thereby producing positive correlation between streamflow and temperature.

Evapotranspiration has very strong positive correlation with temperature in months other than July–October in both the current and future periods. Correlation becomes weaker in July–October and can be negative in August–September (Fig. 3c). These correlations suggest that in months other than July–October, precipitation is not a limiting factor of evapotranspiration and that temperature plays an important role in determining the latent heat flux. In July–October, although the correlation with temperature becomes weak, the correlation of evapotranspiration with precipitation tends to be strong and positive (Fig. 3d). This indicates that precipitation may be important to the variation of evapotranspiration in the late summer–early fall.

Snowmelt has negative correlation with temperature in spring and fall but positive in winter (Fig. 3e). In spring and fall (especially April and October), with temperature increasing, precipitation is more in the form of rain and less in the form of snow. So, for the same amount of precipitation, there will be less snowfall and thus less snowmelt (snowfall can be fully melted in these seasons), hence the negative correlation between snowmelt and temperature. In winter, as mentioned earlier, the higher temperature does not prevent precipitation from being in the form of snow but can make
snowmelt increase, so the correlation between snowmelt and temperature is positive. The correlation of snowmelt with precipitation is always positive in fall, winter, and spring (Fig. 3f). When precipitation increases, the snowfall within the precipitation also increases, so the snowmelt can also increase.

To understand the relative importance of temperature and precipitation in the variations and changes of the hydrological quantities, regressions are made between the interannual variations of hydrological and climate quantities. Assuming each monthly averaged hydrological quantity $S$ is only a function of monthly temperature $T$ and precipitation $P$, we can express the hydrological quantity as $S = S(T, P)$. Then the change of $S(\Delta S)$ due to the changes of $T(\Delta T)$ and $P(\Delta P)$ can be written as

$$\Delta S = \left(\frac{\partial S}{\partial T}\right) \Delta T + \left(\frac{\partial S}{\partial P}\right) \Delta P. \tag{1}$$

If $S$ mainly varies with $T$ or $P$, the relation can be expressed as $S = S(T)$ or $S = S(P)$. Then the corresponding change of $S$ can be written as

$$\Delta S = \left(\frac{dS}{dT}\right) \Delta T, \quad \tag{2}$$

and

$$\Delta S = \left(\frac{dS}{dP}\right) \Delta P, \quad \tag{3}$$

respectively. For the current 38 years and the future 18 years, regressions can be made between $S$ against $T$ and/or $P$. The $dS/dT$ and $dS/dP$ in (2) and (3) can then be approximated as the coefficients of simple regressions of $S$ against $T$ and of $S$ against $P$. The $\partial S/\partial T$ and $\partial S/\partial P$ in (1) can be approximated as coefficients of the multiple regression of $S$ against both $T$ and $P$. These regression coefficients of $S$ against $T$ and $P$ represent change rates, or the production (reduction when negative) efficiencies, of the hydrological quantity with respect to a unit increase of temperature or precipitation.

Simple and multiple regression coefficients for streamflow, evapotranspiration, and snowmelt against temperature and precipitation are shown in Figs. 4 and 5, respectively. The change rates of each hydrological quantity obtained from the simple and multiple regressions are in general very similar. They can vary greatly from month to month, but their seasonal patterns do not change much between the current 38 years and the future 18 years. Therefore, the change rates of the hydrological quantities are relatively fixed in each specific month, and this may be an inherent property of the land–atmosphere system (at least based on this hydrological model).

Streamflow has its largest reduction rate with temperature in May–June (Figs. 4a and 5a). Its production rate with precipitation is maximal in winter and minimal in July–October (Figs. 4b and 5b). The change rates of evapotranspiration with temperature are positive before June and become maximal in June, but they drop to small or negative values in July and the following months (Figs. 4c and 5c). The largest production rates of evapotranspiration with precipitation are in August (Figs. 4d and 5d). The change rates of snowmelt with temperature are negatively large in March–April (Figs. 4e and 5e), and the rates with precipitation are positively large in winter (Figs. 4f and 5f).

The magnitudes of the interannual variabilities of $S$ induced by the interannual variability of $T$ and interannual variability of $P$ can be roughly evaluated with $\mid\partial S/\partial T\mid$ SD($T$) and $\mid\partial S/\partial P\mid$ SD($P$), where SD($T$) and SD($P$), the standard deviations of $T$ and $P$, respectively, provide scales of the year-to-year variations of the climate quantities. Figure 6 presents the 10-model-averaged temperature- and precipitation-induced interannual variabilities of the hydrological quantities, estimated by timing the current- and future-averaged change rates with the current- and future-averaged standard deviations with respect to temperature or precipitation. The variation of precipitation contributes more to the interannual variation of streamflow in November–March, whereas the variation of temperature is more important in May–October. The interannual variation of evapotranspiration is dominated by precipitation in July–October and by temperature in all other months. The interannual variation of snowmelt is dominated by temperature in all snow months except December. Therefore, for the interannual variations of the hydrological quantities, the variations of temperature and precipitation are both important, and their relative importance depends on the month of the year.

5. Change of hydrological cycle and its linkage with warming climate

Figure 7 shows changes of monthly climate and hydrological quantities between the means of the future and current periods. GCMs simulate warming in all months in the UMRB, although the central United States is found to be a “warming hole” compared with surrounding land areas when a regional model was used to downscale GCM results (e.g., Pan et al. 2004). The warming in the second half of the year is higher than the first half, and the maximal warming is in August (Fig. 7a). With the warming, precipitation decreases in summer
but increases in all other seasons (Fig. 7b). Correspondingly, streamflow decreases in all seasons except winter (Fig. 7c), evapotranspiration decreases in July–September and increases in all other months (Fig. 7d), and snowmelt increases in winter but decreases in spring and fall (Fig. 7e).

These results indicate that to the warming in all months, hydrological quantities may have different responses in different months. There is also no apparent consistency throughout the year between the hydrological changes and the change of precipitation. Lettenmaier et al. (1994) also found that the changes of streamflow are not entirely consistent with the changes of the climatic variables. Miller and Piechota (2008) pointed out that, corresponding to the persistent increases of temperature throughout the year, streamflow has increased in some months but decreased in other months.

A general understanding of the linkage between the changes of the hydrological quantities and the changes of temperature and precipitation can be obtained from the correlations between the interannual variations of hydrological and climate quantities. Because streamflow has negative correlation with temperature in all seasons except winter (Fig. 3a) and the temperature increases in all seasons (Fig. 7a), streamflow decreases in all seasons except winter. Meanwhile, streamflow has positive correlation with precipitation in all seasons (Fig. 3b) but precipitation decreases in summer (Fig. 7b), so it seems that precipitation change may contribute to the decrease of streamflow in summer.

Evapotranspiration, which has strong positive correlation with temperature in all months except July–September (Fig. 3c), can be expected to increase in all months except...
Multiple Regressions between Interannual Variations

July–September as well because temperature increases in all months (Fig. 7a). However, in July–September, whereas the correlation of evapotranspiration with temperature becomes weak or even negative, the correlation with precipitation becomes positive (Fig. 3d); thus, with the decrease of precipitation in these months (Fig. 7b), precipitation may contribute to the decrease of evapotranspiration in these months.

Increases of snowmelt in winter can be attributed to the positive correlations of snowmelt, with both temperature and precipitation (Figs. 3e and 3f) and the increases of both temperature and precipitation in winter (Figs. 7a and 7b). Decreases of snowmelt in spring and fall are attributed to the negative correlation between snowmelt and temperature (Fig. 3e) and the increases of temperature in these seasons (Fig. 7a). Precipitation increases (Fig. 7b) and has positive correlation with snowmelt in fall and winter (Fig. 3f), so its role in the decreases of snowmelt is negative.

The linkage between the changes of hydrological quantities and the changes of temperature and precipitation can be better understood by using the change rates of the hydrological quantities inferred from the interannual variations. Because the change rates are nearly identical for the current and future periods, the monthly-mean hydrological quantity $S$ of a specific year in the current $c$ and future $f$ periods can be expressed with the multiple regression coefficients as

$$S_c = \left(\frac{\partial S}{\partial T}\right)_c T_c + \left(\frac{\partial S}{\partial P}\right)_c P_c + a_c + e_c$$  \hspace{0.5cm} (4)

$$S_f = \left(\frac{\partial S}{\partial T}\right)_f T_f + \left(\frac{\partial S}{\partial P}\right)_f P_f + a_f + e_f,$$  \hspace{0.5cm} (5)

FIG. 5. Same as Fig. 4 except that the coefficients are from multiple regressions of hydrological quantities against temperature and precipitation.
respectively, where $a_c$ and $a_f$ are the intercepts in the current and future periods and are in general very close (figures not shown), and $e_c$ and $e_f$ are the errors of this year between $S$ and its regressed value. The means of $S$ over the current 38 years and the future 18 years then become

$$S_c = \left( \frac{\partial S}{\partial T} \right) T_c + \left( \frac{\partial S}{\partial P} \right) P_c + a_c \quad \text{and}$$

$$S_f = \left( \frac{\partial S}{\partial T} \right) T_f + \left( \frac{\partial S}{\partial P} \right) P_f + a_f,$$

respectively, where the means of the errors are zero. The change of the hydrological quantity $S$ from the mean of the current 38 years to the mean of the future 18 years can be written as

$$S_f - S_c = \left( \frac{\partial S}{\partial T} \right) (T_f - T_c) + \left( \frac{\partial S}{\partial P} \right) (P_f - P_c) + (a_f - a_c).$$

Figure 8 presents the seasonal cycles of $S_f - S_c$ (i.e., changes of hydrological quantities from the current to future projected by SWAT (heavy solid line)), and $(\partial S/\partial T)(T_f - T_c)$ and $(\partial S/\partial P)(P_f - P_c)$ (i.e., changes of hydrological quantities contributed by the changes of temperature and precipitation, respectively), with the change rates of multiple (as well as simple) regressions, which are taken as averages of the rates for the current and future periods. The seasonal cycles of the changes of hydrological quantities contributed by the change of temperature and the change rates with respect to temperature from both simple and multiple regressions are overall quite close to those of the changes projected by

![Figure 6. The 10-model-averaged magnitudes of interannual variations of monthly hydrological quantities, estimated by timing the current- and future-averaged regression coefficients with the standard deviations of the respective temperature or precipitation.](image)
SWAT; that is, the line labeled “from T” nearly matches the SWAT line in all months. Both the SWAT prediction and the statistical prediction from $T$ provide the same signs of the changes for all three hydrological quantities and in all months. The change of precipitation through the change rates has small contributions to the changes of the hydrological quantities, especially for evapotranspiration and snowmelt, and the effect also varies from month to month. For example, the change of precipitation has a negative effect on the change of streamflow in spring but a weak positive effect in summer. It may have considerable positive contribution to the decrease of evapotranspiration in August. Therefore, the cross-century changes of the hydrological quantities are dominated by warming, and the influence of the change in precipitation of the same month is much smaller.

While providing better understanding of the relative importance of the changes of temperature and precipitation to the changes of the hydrological quantities, the results of Fig. 8 also suggest that the prediction of the changes of the hydrological quantities can be made, as a complementary approach to numerical modeling, through analyzing the change rates from the interannual variations of the current climate and hydrological cycle. This may simplify future refinements to hydrological predictions as projections of future global climate improve, absent changes of land management in the basin.

Changes in the intensity of the hydrological cycle have been detected (e.g., Ziegler et al. 2003; Yang et al. 2003), and it was reported from recent analyses of observations and modeling that the hydrological cycle has accelerated at high latitudes in the Northern Hemisphere in the twentieth century (Stocker and Raible 2005; Wu et al. 2005). Evaluations of the spectrum of precipitation intensity for the United State reveal that the occurrence of extreme intense precipitation events has increased in the
warming climate (e.g., Groisman et al. 2005; Gutowski et al. 2007). Our calculations also indicate that precipitation in the high end of the intensity spectrum will increase in future (figure not shown). In Fig. 8a, decreases of streamflow from SWAT are overestimated in warm months by the prediction with change of temperature and the change rates. Increased strong precipitation in the future may make streamflow increase, which may partially balance the overestimation of the decrease of streamflow predicted with the change of temperature.

Figure 9 compares the magnitudes of this cross-century changes of temperature and precipitation with the respective interannual variabilities (characterized by the standard deviations) of both the current and future periods. The interannual variability of temperature is relatively constant throughout the year in both the current and future periods. The increases of temperature from the current to the future periods have magnitudes equivalent to the interannual variability in the first half of the year but are much larger in the second half. The interannual variability of precipitation is also relatively constant for all months in both the current and future periods. However, the magnitudes of the changes of precipitation from the current to future are much smaller than (about one-third of) the interannual variability for all months. So, compared with their respective interannual variations, the cross-century rise in temperature is much larger than the change of precipitation.

The analysis presented earlier is based on the ensemble means of the 10-model projections; however, the spread of the model projections also needs to be taken

![Figure 8](image-url)
into account in the assessment. The significances of the changes of different quantities in different months can be measured and compared with the 10-model-normalized mean (NM), which is defined as

$$\text{NM} = \frac{\text{Avg}(X_f - X_c)_i}{\text{SD}(X_f - X_c)_i},$$  

(9)

where \((X_f - X_c)_i\) is the difference between the mean of the future 18 years and the mean of the current 38 years of a climate or hydrological quantity projected from model \(i\), and the Avg and SD represent the average and the biased standard deviation, respectively, over the 10 models. The test statistic for determining the significance of the difference between the averages, which have paired elements, of the future 10-model \((n = 10)\) values and the current 10-model values of the quantity is

$$t = \frac{\text{Avg}(X_f - X_c)_i}{\sqrt{\frac{2}{n}(\frac{1}{2})} \text{sd}(X_f - X_c)_i},$$  

(Wilks 2006), where sd is the unbiased standard deviation over the 10 models. With the definition (9) and the relation \(n(n-1)(\text{sd})^2 = n(\text{SD})^2\), the test statistic can finally be expressed as \(t = 3\text{NM}\). The implication of the NM or the test statistic \(t\) is that, first, for this quantity, if it has a larger change from the current to future periods, then it would be more active in the climate–hydrological system. Otherwise, if it is constant or has little change, it would not be an important factor in the system. Second, it would be better if all or most of the models can project the same or very close changes; if the changes projected are too spread, then the confidence of the projections from the 10 models would be low.

Figure 10 shows the values of the NM for different climate and hydrological quantities. The warming projected by the 10 models is significant in all seasons, and the overall temperature has the most significant changes compared to other quantities. The change of precipitation from the models is significant only in some months, and their significances are much less than that of temperatures. Streamflow has significant decreases in July–September and significant increases in January–February. Evapotranspiration has significant increases in months other than July–September and a significant decrease in

FIG. 9. Absolute values (ABS) of the changes of temperature and precipitation between the future \((f)\) and current \((c)\) periods compared with the standard deviations (SD) of their interannual variations for the current and future periods.

FIG. 10. The 10-model NMs of the changes of climate and hydrological quantities from the current to future. Here, \(\text{NM}_0\) (0.70) is the NM corresponding to the ensemble future–current difference of the 10 models significant at the 0.05 level in two-tailed \(t\) test.
August. Snowmelt has significant decreases in April and October–November and a significant increase in January.

6. Summary and discussion

Hydrological conditions are very important to agricultural and other water-use activities in the UMRB, so the effect of climate change on the hydrological cycle in this basin needs to be assessed. Variabilities and changes of fundamental climate and hydrological quantities in the UMRB from the twentieth century to the twenty-first century are evaluated in this study with data from 10 global climate models in the IPCC (AR4) Data Archive. The ensembles of the climate quantities of the 10 models are fairly close to the observed. The ensembles of the hydrological quantities simulated with SWAT with input from GCM contemporary climate are consistent with those simulated by SWAT with input from the observed climate as well as with those from the NARR. These ensembles suggest that although individual GCMs have less skill in simulating the regional climate and hydrological cycle in the UMRB, the ensemble of multi-GCMs possesses much more skill. Ensemble predictions of the cross-century changes of climate and hydrological quantities, which should be more reliable than from the individual GCMs, are provided. Similar to the results of some previous studies, with warming throughout the year, the precipitation and the hydrological quantities have both increasing and decreasing changes, depending on the month of the year.

The major focus of this study is to understand the linkage between the changes of the hydrological and climate quantities. Correlations between the year-to-year variations of the hydrological and climate quantities can show clues of the linkage. To compare the roles of the changes of temperature and precipitation in the changes of the hydrological quantities from the current to future periods, regressions between the interannual variations of the hydrological and climate quantities are analyzed. The change rates of the hydrological quantities with respect to temperature and precipitation obtained from the regressions reflect the production or reduction efficiencies of the hydrological quantities relative to temperature and precipitation. Simple and multiple regressions both indicate that these change rates can vary greatly from month to month; however, in each month they do not change much from the current to future periods. Evaluations with these change rates for the interannual variations indicate that the variations of temperature and precipitation are both important to the interannual variations of the hydrological quantities, and their relative importance depends on the month of the year.

By using these change rates that remain unchanged from the current to the future years, the changes of the hydrological quantities from the means of the current years to the means of the future years can be decomposed into the contributions from the changes of temperature and precipitation. It is confirmed through this hydrological model that the changes of the hydrological quantities from the current to future periods are dominated by warming in all months, and the contribution from the change of precipitation is in general very small. The warming alone can predict, with the change rates relative to temperature, the major part of the changes of the hydrological quantities. This may provide a complementary approach, to numerical modeling, of predicting the hydrological changes.

The relationships analyzed in this study are for the quantities of the same month. Preliminary results of lagged relationships show that clues for predicting the hydrological changes may be found from the climatic changes of the earlier months, and this will be examined in a future study. The physical processes that control the different responses of hydrological quantities to changes of temperature and precipitation in different month of the year need to be investigated. The relationships between changes of the hydrological cycle and climate found in this study for the UMRB may be different from those of other regions as a result of the specific regional land surface and soil conditions as well as the water management, such as the reservoir constructions and operations. In addition to temperature and precipitation, other climate quantities—such as the humidity, solar radiation, and wind speed—also affect the hydrological cycle. Soil moisture plays an important role in the interaction between the hydrological cycle and atmosphere (e.g., Wu et al. 2002), and it needs to be studied to better understand the physics of the influence of temperature on streamflow. Hay et al. (2002) used output of a regional climate model for hydrologic simulations. In our next study, we will make a comparison between using the output of global and regional models to illustrate the downscaling effect of the regional models in simulating the subbasin-scale climate and hydrological cycle and the ensemble skill of the global models in simulating the basin-scale climate and hydrological cycle.

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REFERENCES


