Potential impacts of global climate change on Tijuana River Watershed hydrology - An initial analysis

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Abstract

During the past year, an investigation has been initiated regarding how future climate changes may impact the hydrology of the Tijuana River Watershed – a binational watershed. The study has used gridded observed daily precipitation and temperatures and downscaled daily precipitation and temperature projections from three global climate models (GCM) to drive the VIC macroscale hydrologic model. Sensitivity analysis using VIC suggests about 2% reduction of runoff for each 1% reduction in precipitation. A 1^{o}C increase in average temperature produces about 3% reduction of runoff. All three GCM simulations yield annual warming, with end-of-century temperature increases from approximately +1^{o}C under a lower emission scenario in the less responsive PCM1 to +3^{o}C in a higher emission scenario with the more responsive GFDL model. Climate projections suggest greater warming in the spring and summer months ranging between 2^{o}C to 3^{o}C under the higher emission scenario. Two of the three GCM simulations yield more frequent summer drying as gauged by VIC simulated soil moisture in the twenty-first century under the higher emission scenario. Summer soil moisture declines most, and most rapidly, in the later part of the twenty-first century. This initial evaluation provides perhaps the first direct estimates of the climate change impacts on the Tijuana River Watershed. However, transforming these results into a more useable projections and impacts will be a task for the future and will require collaboration and interaction between local stakeholders and the researchers.

1. Introduction

The Tijuana River Watershed (TRW) is a binational watershed with an approximately 4500 square km drainage area. About ¼ of the drainage area lies within San Diego County in the United States (U.S.), and the rest lies within Baja California Norte, Mexico (Fig. 1). Originating in Mexico, the Tijuana River runs through several Mexican cities before reaching to Tijuana and then ultimately the U.S. at its estuary on the Pacific coast. TRW is an arid watershed with annual average precipitation totaling little more than 300 mm and highly variable from year to year. About 76% of that precipitation is simulated as being lost to evapotranspiration.

In response to assumptions of continuing anthropogenic increases in global greenhouse-gas emissions to the atmosphere, twenty-first Century temperatures in California are simulated to increase by between +2^{o}C and +6^{o}C more by end of century, depending on the climate model and particular assumptions about emission rates used. There is much less consensus regarding either the sign or magnitude of attendant changes in precipitation patterns (Cayan et al. 2008). With these climate changes, it is expected that there may be more frequent drought across the Southern California/northern Baja region. It is crucial to understand how the projected climate changes would affect hydrological conditions in the TRW, which is an important hydrologic/environmental feature of the cities and communities in the basin and is home to diverse ecosystems, especially at its downstream estuary. This report describes an initial research study with aiming to address the following specific research questions:

a) what is the sensitivity of simulated runoff across the TRW region to climate warming (as a result of arbitrarily prescribed perturbations of the observed history of meteorology?

b) how large are simulated changes in runoff and soil moisture regimes in the TRW region under the influences of the specific climate changes projected by a set of IPCC AR4 climate models?

2. Datasets, Models, Methods

2.1 Observed meteorology

Historical daily gridded meteorological observations of precipitation (P), maximum daily temperature (T_{max}), minimum temperature (T_{min}), and wind speed at 1/8 degree spatial resolution across TRW were obtained from the Surface Water Modeling Group at the University of Washington (http://www.hydro.washington.edu). A description of the preparation of this dataset can be found in Maurer et al. (2002). The Maurer et al. (2002) dataset is available for the period 1949 through 2000, but hydrologic simulations were driven for the period 1950-1999 in this study.

2.2 Global climate models and downscaled scenarios

Climate change projections for the twenty-first century were obtained from three coupled ocean-atmosphere global-climate models (GCMs) previously used in the IPCC Fourth Assessments (IPCC 2007). GCM projections are made at coarse spatial scale (with grid cell centers separated by one to two degrees of latitude and longitude or 100 to 200 km) (Dettinger 2004; Maurer 2007). Daily precipitation totals (P) and daily maximum and minimum temperatures (Tmax, Tmin) from three GCMs (the French CNRM CM3 model, American GFDL CM2.1 and American NCAR PCM1 models) form the basis of the present study. We analyzed projections of climate variations and trends, for 2000-2099, under a medium-high emission scenario (SRES A2) and a low-emission scenario (SRES B1) in this study.

A statistical downscaling method called constructed analogues (Hidalgo et al. 2009) was used here to estimate local-scale surface weather, on an 1/8-degree (12-km) grid, from the coarse-scale atmospheric simulations provided by the GCMs. In the constructed analogues (CA) method, high-resolution daily climate patterns are obtained by constructing linear combinations of full-resolution, previously-observed weather patterns, with the particular linear combinations used on each day determined from the combination of coarse-resolution versions of those patterns that best fit the GCM output on that day. Limited bias corrections were applied to the downscaled results to ensure that observed monthly normals of precipitation and temperatures were maintained.

2.3 Macroscale hydrologic model

Responses of the TRW hydrologic system to various climates were simulated using the Variable Infiltration Capacity (VIC) land-surface hydrological model (Liang et al. 1994). VIC is a distributed macro-scale hydrological model originally developed at the University of Washington and Princeton (Liang et al. 1994). VIC simulates a full complement of hydrological variables, based daily meteorological data as time-varying inputs and specified soil and vegetation properties as time-invariant model parameters. The land surface is modeled using a tiled configuration of vegetation covers, while the subsurface flow is modeled using three soil layers of different thicknesses (Liang et al. 1994). Defining characteristics of VIC are the probabilistic treatment of sub-grid soil moisture capacity distribution, the parameterization of baseflow as a nonlinear recession from the lower soil layer, and unsaturated hydraulic conductivities at each particular time step that are functions of the degree of saturation of the soil (Liang et al. 1994).

The VIC model was run at a daily time step in “water balance mode” at a 1/8 by 1/8 degree grid resolution using model parameters taken from datasets developed for the Land Data Assimilation Systems (Mitchell et al. 1999). Interested readers can refer to Mitchell et al. (1999) and Maurer et al. (2002) for discussions of model parameters.

2.4 Methods

VIC was forced using the observed gridded meteorology (Maurer et al. 2002) from 1950 to 1999, and the downscaled GCM data from 1950 to 2099. Twenty-seven 12-km VIC grid cells represented (approximately) drainage area of the Tijuana River Watershed (Fig. 1).

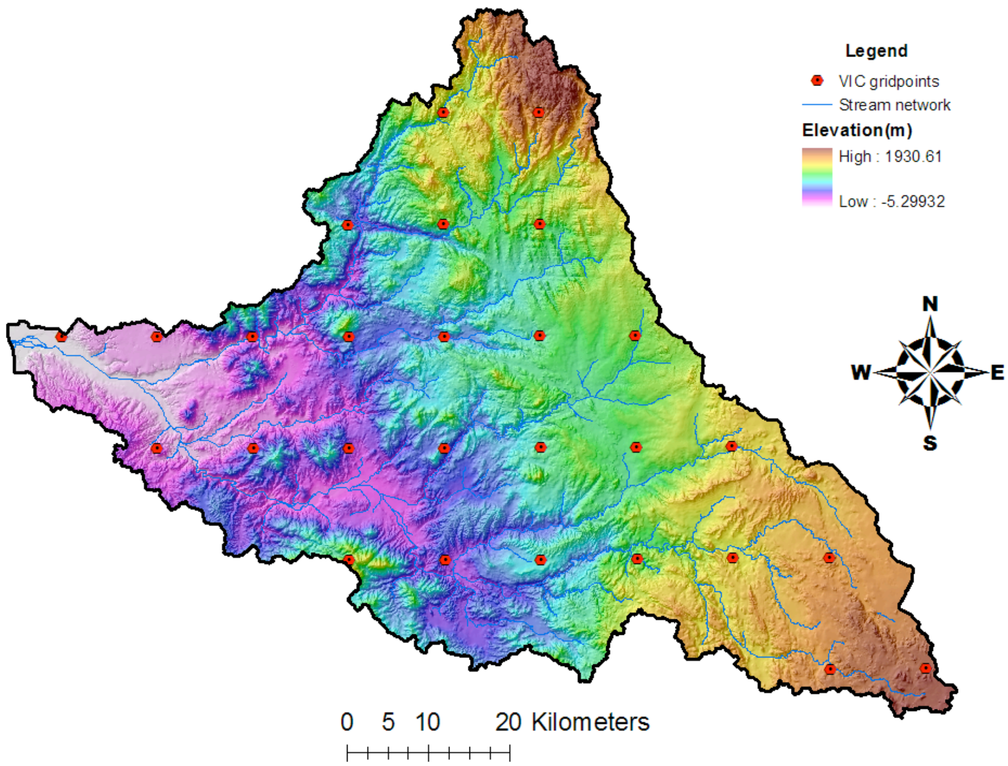

Fig. 1 Tijuana River Watershed. Red circles represent the 27 1/8-degree VIC grid cells approximating the Tijuana River Watershed. Elevations and watershed boundary obtained from the Tijuana River Watershed GIS Database project at San Diego State University.

We begin the analysis by evaluating runoff sensitivities to warming and drying. Precipitation elasticity is a measure indicating change in runoff per unit rainfall change, while temperature sensitivity is the change in runoff per unit temperature change. To compute runoff changes under altered climate, we developed six hypothetical scenarios, as shown in Table 1, and then have computed temperature sensitivities and precipitation elasticities by determining the percentage change between the runoff simulated with the historical meteorology incremented by a unit change in either temperature or precipitation, and the runoff simulated using the historical meteorology, for the period 1961-1990. For example, if Q_1 is the average runoff simulated by VIC when maximum and minimum temperatures are elevated uniformly by

+1^{o}C (holding the precipitation unchanged) and Q is the VIC runoff simulated using historical meteorology:

Sensitivity (in %) = $((Q_1\text{-}Q)/Q)*100$

To compute precipitation elasticity, we increase or decrease precipitation uniformly (holding temperatures unchanged) to compute runoff by VIC. This runoff was then compared with the VIC runoff simulated under observed meteorology using the procedure described above.

Table 1 Hypothetical climate change scenarios applied to the historical observed meteorology

Scenario	Details
Scenario1	Imposed 1^{o}C warming to daily maximum and minimum temperature used to drive the VIC
Scenario2	Imposed 2^{o}C warming to daily maximum and minimum temperature used to drive the VIC
Scenario3	Imposed 3^{o}C warming to daily maximum and minimum temperature used to drive the VIC
Scenario4	Imposed 10% uniform increase to daily precipitation used to drive the VIC
Scenario5	Imposed 10% uniform decrease to daily precipitation used to drive the VIC
Scenario6	Imposed 2^{o}C warming to daily maximum and minimum temperature and 10% uniform decrease to daily precipitation simultaneously used to drive the VIC

The monthly and annual data of the downscaled climate model projections and associated VIC simulations were also analyzed to understand how large the corresponding changes in runoff and soil moisture regimes might be in the TRW region under current projections of climate change.

3. Results

3.1 Historical observational, *1950-1999*

Water year (October through next year September) total precipitation varies from 160 mm to 560 mm in the period 1951 through 1999, with an average value of 310 mm and standard deviation of 105 mm. About 76% of annual precipitation, on average, is simulated as being lost to evapotranspiration under the historical forcings. Thus only 24% of annual precipitation leaves the watershed as runoff (Fig. 2).

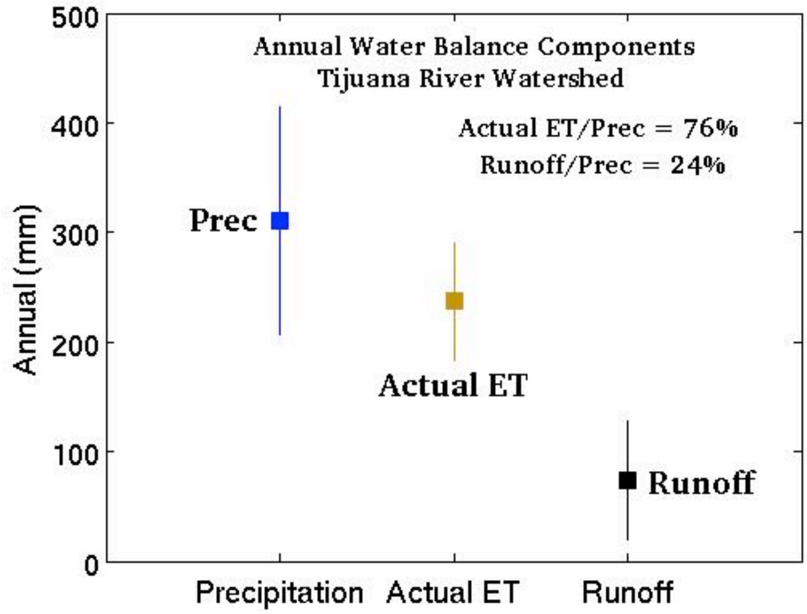

Fig. 2 Long term averages of annual precipitation, simulated annual evapotranspiration and simulated annual runoff for the Tijuana River Watershed under historical (water years 1951-1999) conditions. Vertical whiskers extend to +/- one standard deviation.

About 90% of the precipitation falls from October through April, with maximum precipitation falling in January (65 mm). Annual temperatures vary from 12.5°C to 15.2°C, averaging 13.5°C, historically. Monthly temperatures varied from 7.7°C to 20.7°C, with maximum temperature is in August. Fig. 3 illustrates annual precipitation, June-July-August average temperatures, and simulated annual soil moisture and annual runoff from 1951 through 1999. During the historical period from 1951-1999, five years in a row in the later part of twenty-century had summer temperatures that were in the warmest tercile of historical temperatures (Fig. 3).

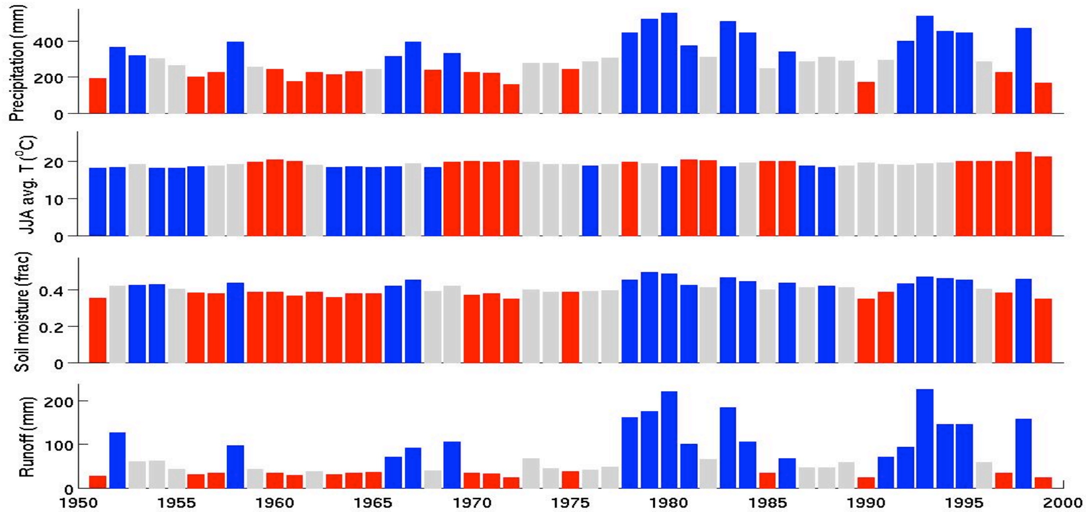

Fig. 3 Water year precipitation, June-July-August average temperature, simulated water year soil moisture and annual runoff for the Tijuana River Watershed from 1951 through 1999. For precipitation, soil moisture, runoff, bars are colored red if the value is below one-third of the historical (1961-1990) values and blue if the value is above two-thirds of historical values. This color scheme is reversed for temperatures. Soil moisture and runoff are simulated using a macro scale hydrologic model VIC, driven by observed meteorology

3.2 Sensitivity analysis, *1950-1999*

Sensitivity experiments suggest that warmer temperatures decrease runoff. Specifically, a 1^{o}C increase in average temperature produced about a 3% reduction in runoff, a 2ºC warming yielded about 6% less runoff and a 3ºC warming yielded about 8-9% less runoff (Fig. 4).

Reductions in precipitation also reduced runoff. In the VIC simulations, a 10% reduction of precipitation led to, on an average, roughly a 20% reduction in runoff (Fig. 4).

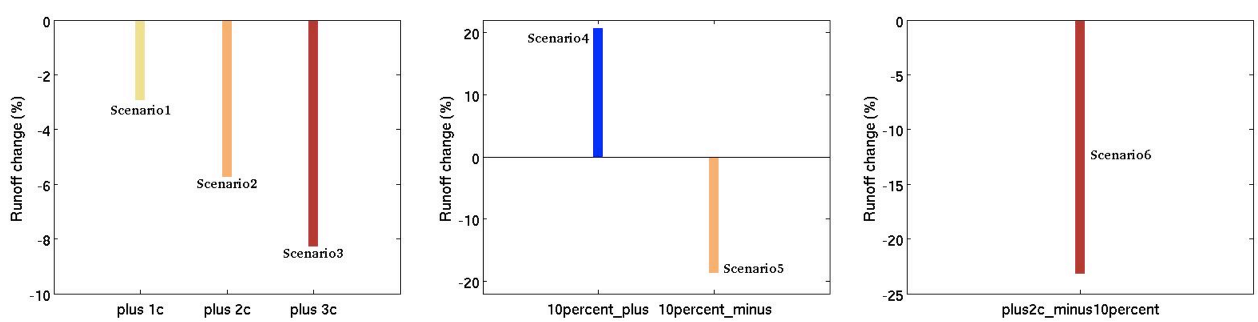

Fig. 4 Changes in annual runoff as a function of hypothetical (specified) temperature changes to the historical meteorology (*Left*), hypothetical precipitation changes (*Center*) and specified changes in temperature and precipitation simultaneously (*Right*). Changes are computed with respect to climatologically (1961-1990) average simulated by VIC driven by observed meteorology

The reduction of annual runoff in the hypothetical warming scenarios was due to runoff reductions in January through May (Fig. 5). There were increases in evapotranspiration from January to May, but after that evapotranspiration declined because no or little soil moisture remained available for evapotranspiration to draw upon from the persistently dry soils (Fig. 5).

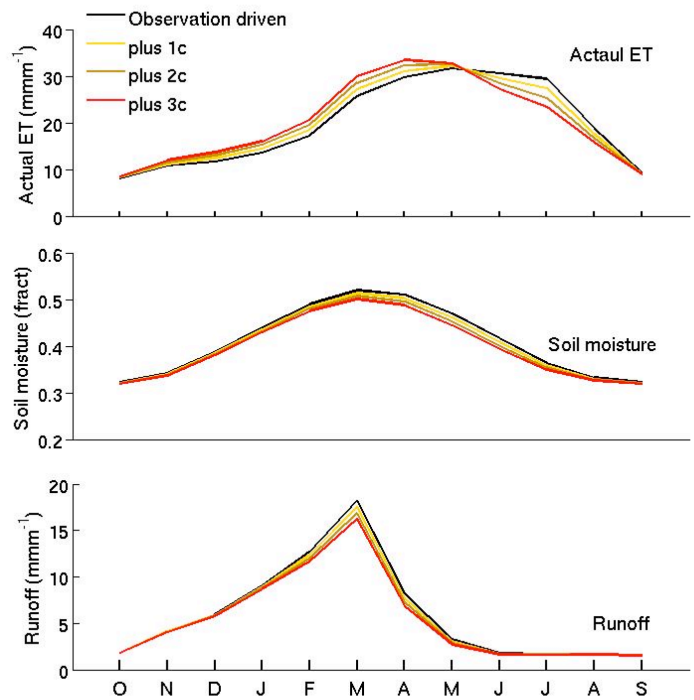

Fig. 5 Monthly averages of simulated evapotranspiration, soil moisture and runoff under historical and modified-historical meteorologies. Black curves represent 1961-1990 mean monthlies simulated by *VIC* driven by observed meteorology; yellow, gold and red color curves represent corresponding values from simulations with 1, 2 and 3ºC warmer conditions applied.

Under a hypothetical scenario with both 2^{o}C warming and 10% reduction of precipitation, runoff declined by about 23% reduction of runoff (Fig. 4 *Right*). Fig. 6 (panel *d*) compares runoff simulated by VIC under the hypothetical scenario with warming of 2^{o}C and 10% reduction of precipitation (scenario 6 in Table 1) to runoff simulated as driven by observed meteorology. Runoff differences vary spatially across the watershed, with higher sensitivities in the parts of the watershed with higher precipitation (panel *a*) and higher runoff generation (panel *c*). Notably these higher sensitivity areas are mostly in the northern part of the watershed and north of the US/ Mexico border.

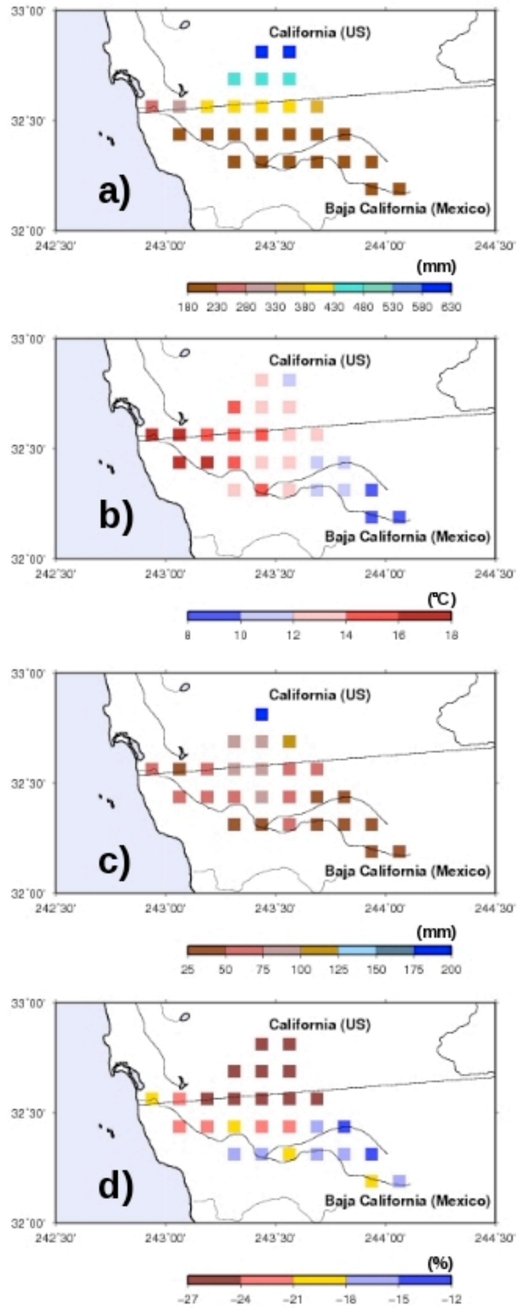

Fig. 6 Tijuana River Watershed: a) annual precipitation (mm) b) annual temperature (^{o}C) c) annual simulated runoff (mm) d) compares runoff simulated by VIC under the hypothetical scenario with warming of 2 ^{o}C and 10% reduction of precipitation to runoff simulated as driven by observed meteorology

3.3 Climate change projections, *1950-2099*

Water year precipitation and annual temperature values, as deviations from model simulated historical (1961-1990) normals, from the three GCMs, over the TRW are depicted in Fig. 7. The changes in annual precipitation and temperature were computed using the area-averaged precipitation and temperature of the VIC grid cells approximately covering the TRW. GCMs used in this study cover a range of climate change sensitivities. All the three simulations yield annual warming, with end-of-century temperature increases from approximately +1^{o}C under the lower emission scenario in the less responsive PCM1 to +3 ^{o}C in the higher emission scenario with the more responsive GFDL model. Because of naturally occurring decadal and multi-decadal precipitation variations, as well as differences between the GCMs, trends in precipitation projections are less steady or unanimous. The GFDL and CNRM models project about 3% to 10% decrease in precipitation, by 2099. PCM shows about 15% of increase in precipitation by 2099. However, these precipitation differences are all within the variability of annual precipitation, as shown in Fig. 8.

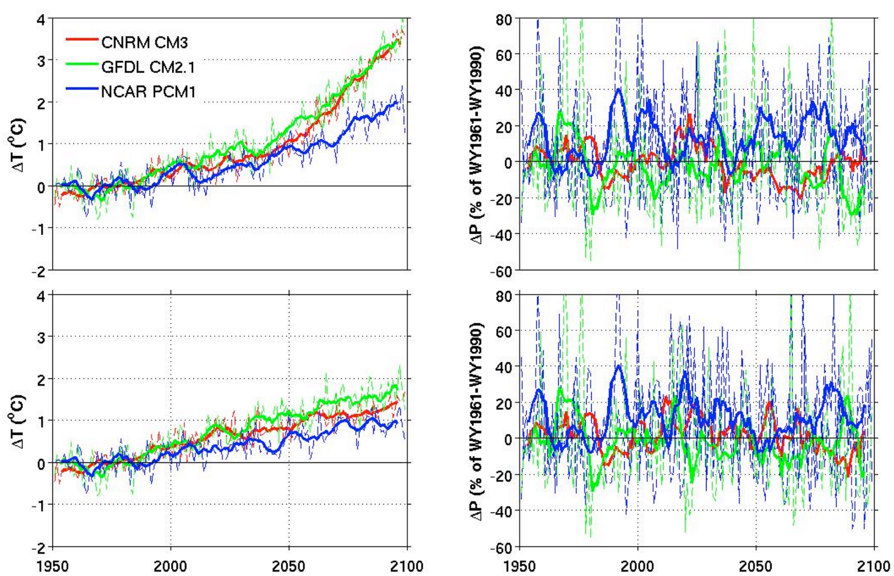

Fig. 7 Ensembles of historical and future temperature and precipitation projections for the Tijuana River Watershed from three coupled ocean-atmosphere general circulation models, each forced by historical and twenty-first century A2 and B1 greenhouse-gas emission scenarios. Solid curves are 7-year moving averages and dashed curves are annual deviations. All values are plotted as deviations from the means for 1961-1990. Top panels from SRES A2 and bottom panels from SRES B1. (*Left*) Temperature, (*Right*) Precipitation

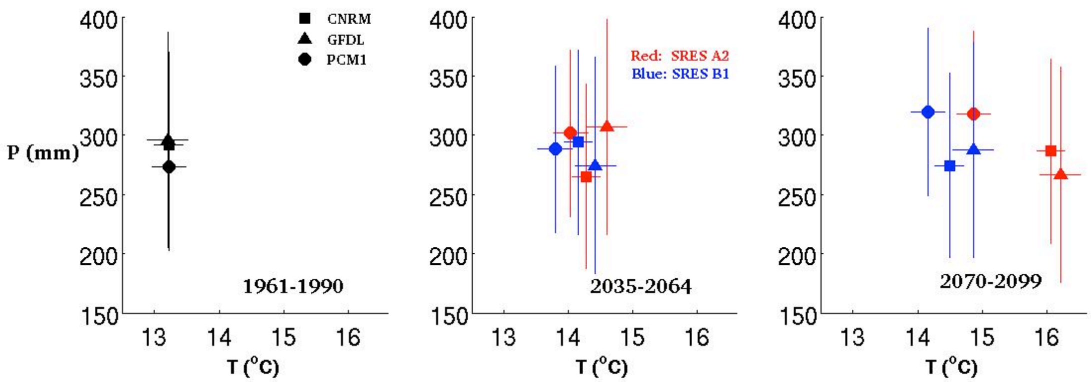

Fig. 8 Plots of annual precipitation versus annual temperature for three coupled ocean-atmosphere general circulation models forced by historical and twenty-first century A2 and B1 greenhouse-gas emission scenarios. (*Left*) for the period 1961-1990 (*Center*) for the period 2035-2064 (*Right*) for the period 2070-2099. In the panels "squares", "triangles" and "circles" symbols show the simulations from CNRM CM3, GFDL CM2.1 and NCAR PCM1, respectively. Red symbols are for the A2 emission scenario and blue symbols are for the B1 emission scenario. Horizontal and vertical whiskers extend from +/- one standard deviation. For precipitation, standard deviation is computed from the detrended timeseries of annual precipitation. For temperature, standard deviation is computed from the annual average temperature timeseries, but after 30-years high pass filter

In 2070-2099, both the CNRM CM3 and GFDL CM2.1 models project thirteen annual precipitation values that are in the lowest tercile, compared with ten from 1961-1990. The NCAR PCM1 model yields only six annual precipitation values, for 2070-2099, that are in the lowest tercile (Fig. 9). All the three simulations suggest more summer warming in the twenty-first century under the higher emission scenario (Fig. 10). Not a single summer is marked as a cool summer after about 2025. Under the climates from two of the three climate models, VIC yields more frequent summer drying as quantified by simulated JJA average soil moistures in the lower (historical) tercile range (Fig. 11). This summer drying is largely controlled by precipitation, but also is probably amplified by overall warming (Figs. 9, 10, 11).

Water year runoff, for 1951-2099 and as simulated by VIC in response to the GCM climate projections, is depicted in Fig. 12. Under two of the three GCMs, VIC runoff declines in the period 2070-2099 as compared to 1961-1990. The CNRM model projects about 8% reductions, while the GFDL model projects about 25% decrease, and the PCM1 model projects about 30% increase in simulated runoff by 2099.

Fig. 13 shows mean monthly precipitation from historical simulations, and mean changes in precipitation projected under A2 emission scenario, averaged over the three coupled ocean-atmosphere general circulation models. April declines by end of century to a statistically significant extent. Monthly precipitation increases in October, July and September are significant by 2099 (Fig.13). There are significant increases of temperature in all months, with most warming in the spring and summer months ranging between 2^{o}C to 3^{o}C under the higher emission scenario (Fig. 14).

The summer drying, illustrated in Fig. 11, is also evident in Fig. 15, which presents the mean changes in monthly soil moisture projected under A2 emission scenario from the three climate models. The deficit in summer soil moisture grows especially in the last third of the twenty-first century (Fig. 15). Projected changes in monthly runoff are significant only in Aprils (Fig. 16).

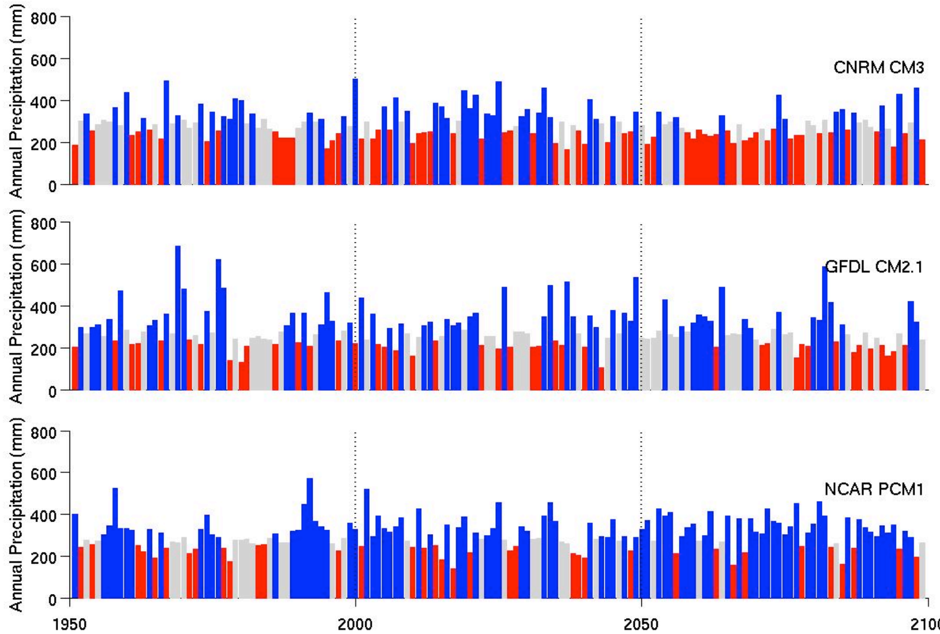

Fig. 9 Water year precipitation, 1951-2099, from three coupled ocean-atmosphere general circulation models, each forced by historical and twenty-first century A2 greenhouse-gas emission scenario. Bars are colored red if annual precipitation is in the lowest (historically determined) tercile, and blue if in the upper historical tercile.

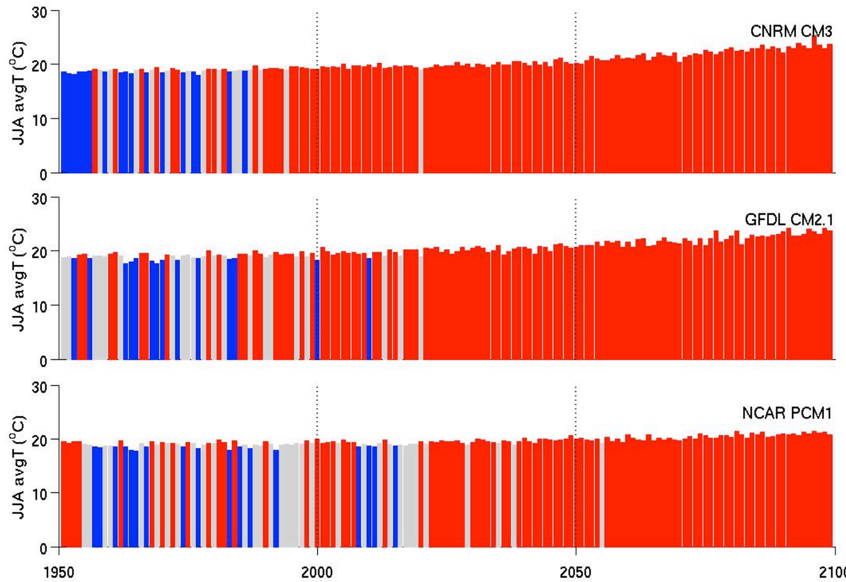

Fig. 10 June-July-August average (JJA) temperature from three coupled ocean-atmosphere general circulation models forced by historical and twenty-first century A2 greenhouse-gas emissions. Bars are colored red if JJA temperature is in the upper historical tercile, and blue if in the lower tercile; note that this coloring scheme is opposite of Fig. 9.

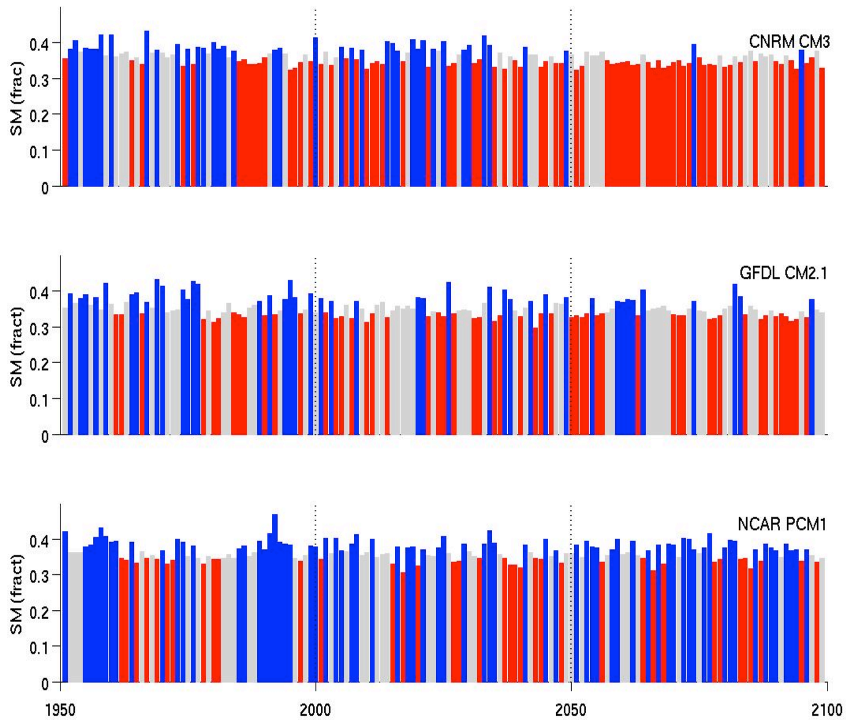

Fig. 11 Same as Fig. 9, except for the simulated JJA soil moisture (as fraction of porosity).

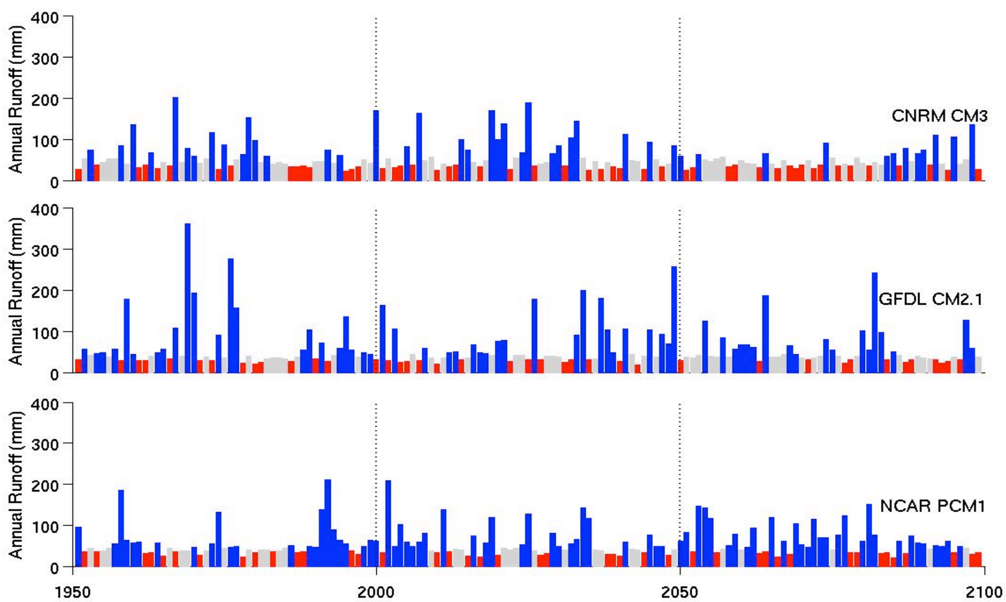

Fig. 12 Same as Fig. 9, except for the simulated annual runoff.

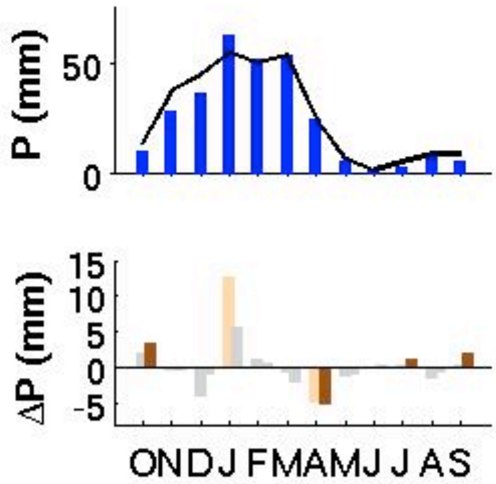

Fig. 13 Mean monthly precipitation and changes thereto. In top panel, bars represent 1961-1990 mean monthly precipitation averaged over three coupled ocean-atmosphere general circulation models. The solid line in the top panel shows the climatologically (1961-1990) monthly precipitation computed from historical data. The bottom panel shows the mean changes in precipitation projected under A2 emission scenario averaged over the three coupled ocean-atmosphere general circulation models. In the bottom panel, each month has two bars, with the first bar indicating mean changes from 1961-1990 by 2035-2064 and the second bar indicating changes by 2070-2099. Bars are marked with dark color if the changes are statistical significant using the Student's two-tailed t-test (at p = 0.10 confidence level).

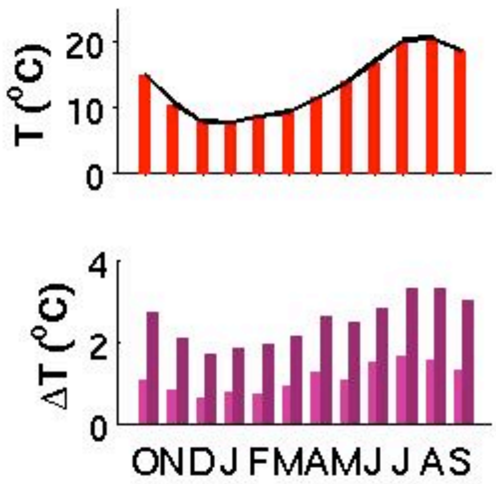

Fig. 14 Same as Fig. 13, except for temperature

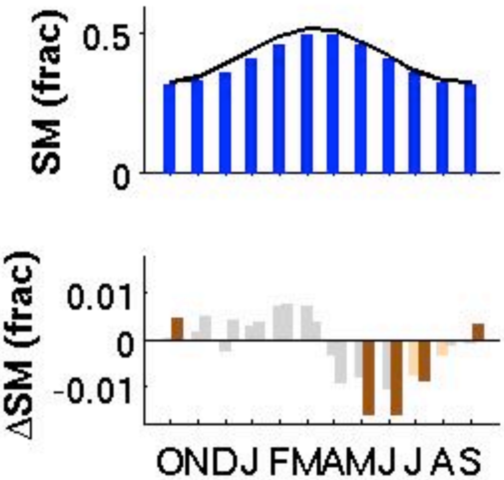

Fig. 15 Same as Fig. 13, except for simulated soil moisture.

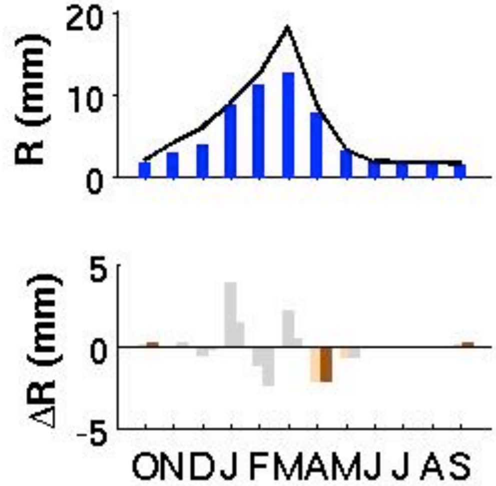

Fig. 16 Same as Fig. 13, except for simulated runoff.

4. Discussion

This study investigates how future climate changes might impact hydrology in the Tijuana River Watershed. The study uses observed historical gridded daily precipitation and temperature (Maurer et al. 2002) and downscaled daily precipitation and temperature simulations from three global climate models (GCMs) to drive a macro scale hydrologic model (VIC). The downscaled future projections were used to evaluate future changes in monthly and annual precipitation and temperature for the TRW. All the three simulations yield annual warming, with end-of-century temperature increases ranging from approximately +1^{o}C under the lower emission scenario in the less responsive PCM1 to +3 ^{o}C in the higher emission scenario with the more responsive GFDL model. Because of naturally occurring decadal and multi-decadal precipitation variations as well as differences among the GCMs, trends in precipitation projections are less obvious and not unanimous. The varied results emphasize the uncertainties related to the present generation of GCM's, that are manifested in different magnitudes of warming and quite strongly different changes (positive to negative) in precipitation over the twenty-first Century.

Sensitivity analysis using the VIC suggests reduction of runoff when precipitation is decreased or when temperatures are increased. A 10% reduction of precipitation leads to, on an average, about a 20% reduction of runoff. A 1^{o}C increase of average temperature produces about 3% reduction of runoff. VIC runs forced by GCM climate change simulations suggest possible directions and rough magnitudes of changes in monthly and annual model soil moisture and runoff that might be associated with current climate projections. Two of the three simulations analyzed in this study yield more frequent summer drying in the Tijuana River Watershed under the higher emission scenario. The projected change in monthly runoff is significantly different from the simulated natural climate variations only in April. Temperatures increase significantly in all months, with most warming in the spring and summer months.

Considering the intermittent nature of Tijuana River flows, an investigation of possible changes in extreme streamflow under climate change would be interesting, but was not attempted here because of the use of coarse resolution macroscale hydrologic model. This evaluation provides perhaps the first direct estimates of the climate change impacts for the TRW region. However, VIC is a macro scale hydrologic model and its use in the present study is to assess, through a rather coarse lens, the tendencies that might occur under climate changes. Transforming these hydrological responses into an estimate of streamflow at key locations of the region will be a task that will have to follow the study described here, and will require direct collaboration and interaction with local stakeholders and researchers, for example San Diego Water Authority, City of Tijuana, the Center for Scientific research and Higher Education of Ensenada (CICESE) and Mexican Institute of Water Technology (IMTA) in Mexico.

5. Acknowledgments

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