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IMPACTS OF CLIMATE CHANGE ON HYDROLOGIC INDICES IN A NORTHEAST KANSAS WATERSHED

C.B. Siebenmorgen, A.Y. Sheshukov, K.R. Douglas-Mankin

ABSTRACT

Great Plains watersheds contribute to the diminishing North American unpolluted surface water supply as well as provide habitat for a number of threatened or endangered species. The number and size of these important systems has been greatly reduced by agriculture and urbanization. Climate change could pose an even greater threat to these endangered systems. There are many climate change scenarios that predict varying changes in future temperature and precipitation amounts for the Great Plains Region. In this study, two Global Climate Model (GCM) scenarios were analyzed to determine monthly rainfall and precipitation trends from 2000 to 2100. The trends were applied to the actual monthly precipitation and temperature distributions in a Northeast Kansas watershed. Daily weather data were simulated for 100 years using the WINDS weather generator. These simulations were input into the Soil and Water Assessment Tool (SWAT) hydrologic model. The streamflow output from these simulations was input into the Indicators of Hydrologic Alteration (IHA) software, which calculated multiple hydrologic indices that were compared back to a baseline scenario. The analysis showed that these climate change scenarios caused a varying increase in mean monthly streamflow patterns as well as a reduction in low flow occurrences and durations. Flood frequency and duration showed varying changes based on the individual scenario. This analysis shows that climate change scenarios have an effect on terrestrial and aquatic ecosystems in the Great Plains Region.

KEYWORDS. Climate Change, GCM, Hydrologic Indices, SWAT

INTRODUCTION

Great Plains stream systems represent part of the diminishing North American unpolluted surface water supply and provide habitat for a number of threatened or endangered species (Dodds et al., 2004). These Great Plains systems once encompassed 160 million ha, but are now considered one of the most endangered biomes on the continent. Much of the Great Plains is now heavily affected by agriculture and urbanization and climate change could increase the risk to these endangered systems.

Current Global Climate Model (GCM) scenarios predict changes in future temperature and precipitation amounts for the Great Plains. However, the consequences of these GCM scenarios cannot be fully evaluated based on only precipitation and temperature changes. The goal of this study was to simulate the impact of climate change in Northeast Kansas on hydrologic indices. The study area was a watershed unregulated by large dams/reservoirs to allow streamflow assessment.

With the numerous available hydrologic indices, narrowing down which indices were relevant was critical. Olden and Poff (2003) conducted an in-depth review and redundancy test of 171 different indices. This review concluded by explaining that for a certain stream type, the flow regime can be adequately classified with 2-4 hydrologic indices. Furthermore, Aguilar (2009) studied the historic changes of 12 ecologically relevant hydrologic indices in Kansas streams. The fact that some indices have both positive and negative effects on ecosystems makes in-depth ecological hydrologic indices analysis very difficult (Aguilar, 2009). For this reason, this study only presented the change in hydrologic indices and their potential ecological effects for several climate change scenarios, and an in-depth ecological analysis was not performed.

STUDY AREA

The area used for this study was the Soldier Creek Watershed (HUC 10: 1027010208), which drains part of Nemaha, Jackson and Shawnee counties in northeast Kansas (fig. 1). This unregulated watershed covers approximately 76,931 ha. The Soldier Creek Watershed land use is dominated by pasture and cropland. Most of the cropland and forest land within the watershed are located near the streams. Slopes are generally gentle sloping with a median slope of 2.5%. Soils in this area are generally silt loam, clay loam or silty clay loam with a mean permeability around 1.3 cm/h.

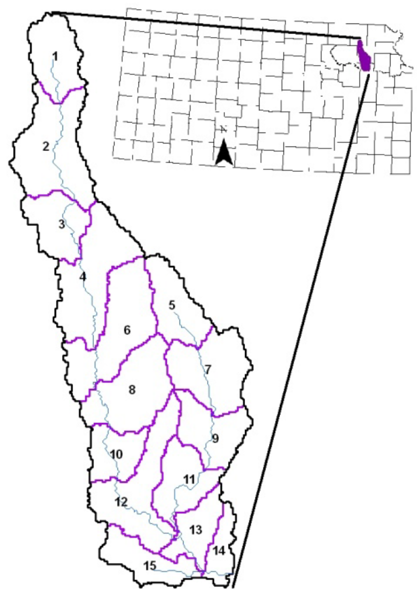

Figure 1. Soldier Creek Watershed, Kansas.

Soldier Creek is a meandering stream with steep bank slopes. Parts of the stream network have been subject to human alterations through channelization, low-water crossings and urbanization. These alterations have lead to extreme channel degradation throughout the watershed (Juracek, 2002). The outlet of the watershed discharges into the Kansas River north of Topeka.

CLIMATE CHANGE SCENARIOS

GCMs are usually developed on a global grid with grid-cells of about 50,000 km^2 to predict possible future scenarios in response to rising concentrations of greenhouse gases among other climate change driving forces. One of the GCM models, the National Center for Atmospheric Research Community Climate System Model (NCAR CCSM) generates various climate change projections on a 1.4° grid-cell global Gaussian grid. The CCSM model simulates changes in atmosphere, oceans, sea ice, and land surface, and for every grid-cell generates physical output variables on the monthly time-step. Average air temperature and precipitation depth are the model outputs used in this study. Outputs of the CCSM model are relatively coarse for watershed scale modeling, and a spatial downscaling procedure is needed to project the results to local scale. For the CCSM model the statistical spatial downscaling was conducted based upon the PRIZM climate mapping system (Daly et al., 1994) and resulted in outputs defined on 4.5×4.5 km^2 grid-cells. The downscaled monthly temperature and precipitation data for climate change projections is available in geospatial format at the NCAR website (NCAR, 2008).

There were 15 to 25 downscaled CCSM grid cells in the Soldier Creek Watershed. The grid-cell closest to the closest weather station to the watershed was selected and climate data from ensemble averages of the 20th century experiment and various climate projections was collected into the monthly series from 1980 to 2100. Climate change scenarios A1B and A2 represent two possible scenarios, both exhibiting global increase of annual temperature and precipitation. For Northeast Kansas the A2 ensemble average shows an annual increase of about 3°C and 100 mm in 2100 compared to 2000 (Figure 2). While annual increase is important for watershed management, within-year variations, like monthly changes, present more detailed information of the projected climate changes. Thus, after collecting downscaled CCSM output data for each month individually and calculating a linear regression fit for each climate variable F_{trend} we obtain

$$F_{trend}(t_m, t_y) = a_0(t_m) + a_1(t_m)t_y$$

where t_m is the month, t_y is the year, and intercept and slope coefficients a_0 and a_1 vary with month. Coefficients a_0 and a_1 are listed in table 1 for A1B and A2 scenarios. For either scenario the temperature increase is small and spread over all months almost uniformly, while the precipitation depths tend to grow significantly in spring and fall and decrease in winter months.

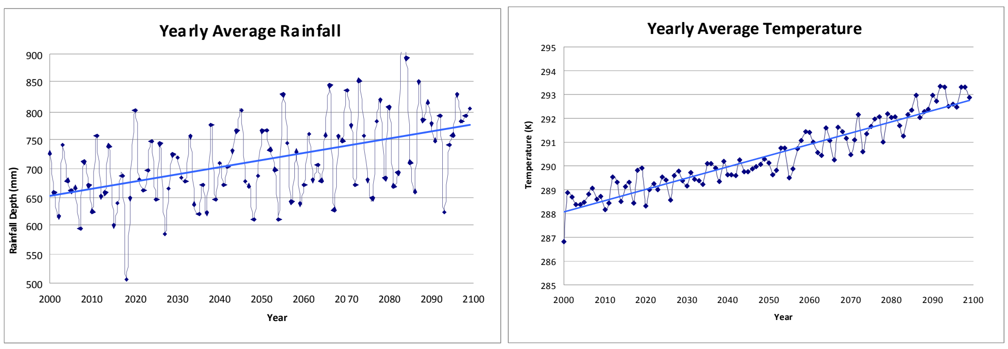

Figure 2. Regression fits for mean annual temperature and precipitation depth of A2 scenario for North-Eastern Kansas.

Table 1. Trend coefficients and percent increase of GCM developed monthly changes in temperature and precipitation by the year 2100.

			Month												Year
		Scenario	1	2	3	4	5	6	7	8	9	10	11	12	
Temperature	a_0		201.22	216.23	229.24	253.18	250.64	240.28	244.71	233.36	235.45	226.94	228.74	224.29	193.30
	a_1		0.04	0.03	0.03	0.02	0.02	0.03	0.03	0.04	0.03	0.03	0.03	0.03	0.05
	A1B (%)	1	1.31	1.08	0.93	0.62	0.74	0.97	0.97	1.18	1.06	1.08	0.92	0.92	0.98
	A2 (%)	2	1.37	1.81	1.40	1.25	1.33	1.56	1.89	1.89	1.89	1.98	1.73	1.59	1.64
	A1B UNI (%)	3	0.98	0.98	0.98	0.98	0.98	0.98	0.98	0.98	0.98	0.98	0.98	0.98	0.98
Precipitation	a_0		67.62	141.30	-36.09	-457.62	-316.52	-77.16	-269.64	-67.54	-169.31	-59.68	117.24	78.06	-1862.80
	a_1		-0.02	-0.05	0.04	0.26	0.21	0.10	0.17	0.05	0.10	0.05	-0.04	-0.02	1.26
	A1B (%)	1	-5.34	-14.93	8.81	40.50	20.98	8.05	22.03	14.64	34.05	13.04	-7.97	-4.64	10.77
	A2 (%)	2	-17.49	-16.00	17.34	36.94	45.44	22.96	4.02	24.73	44.02	-3.28	5.24	34.82	16.56
	A1B UNI (%)	3	10.77	10.77	10.77	10.77	10.77	10.77	10.77	10.77	10.77	10.77	10.77	10.77	10.77

Downscaling monthly GCM projections to daily scale involved the use of a weather generator. One model, called WINDS (Weather Input for Non-point Data Simulations) (Wilson et al., 2006), represents a stochastic weather generator that simulates many years of weather realization based on statistical characteristics computed from the (sub)daily time series of historical records. The statistical characteristics such as mean, standard deviation, and skewness coefficient are calculated for eleven climate variables: daily minimum and maximum temperature and relative humidity, average and maximum wind speed, wind direction, solar radiation, atmospheric pressure, and precipitation depth, and are represented by cosine functions with three harmonics:

$$W(t_j) = W_{mean}\left(b_0 + b_1\cos(t_j + b_2) + b_3\cos(2t_j + b_4) + b_5\cos(3t_j + b_6)\right),\ \ t_j = 2\pi(\text{day}_j)/365$$

where W is the statistics of climate variable, W_{mean} is the annual mean value, and b represents harmonic coefficients. Non-precipitation climate variables are represented by continuous functions and simulated within a statistical framework of Markov processes. Discrete precipitation events are modeled using a first-order, two-state Markov chain based on a transitional probability of wet given wet days and dry given wet days.

To account for climate change, year 2100 from the projected trends was selected as a future climate state and percent change in temperature and precipitation for 2100 was calculated based on the trend coefficients and presented in table 1. Monthly changes for A1B and A2 scenarios were incorporated in WINDS calculations. At each step of generating daily variables, the normalizing parameter representing annual average value of the specified variable was scaled according to the monthly shifts (table 1) and the new value was generated. Standard deviations and transitional probabilities were not modified and kept equal to the values calculated by WINDS. While annual scaling was not included in climate predictions, natural variability in daily values associated with standard deviations and transitional probabilities was incorporated in the model. The WINDS model was run for 100 years and daily values of minimum and maximum temperatures and precipitation were generated for four simulation scenarios.

<u>Scenarios</u>

The following scenarios were simulated in this study:

Calibration run – This scenario incorporated NCDC weather station data from 1980 to 2000. Main purpose of this run was to calibrate the watershed model against available streamflow data. Calibrated parameters were then used in future climate change scenarios.

Baseline – The baseline scenario consisted of daily values generated by WINDS without applying any climate change trends. It represented baseline hydrologic conditions that were compared against three climate change scenarios.

Scenario 1 – Climate change Scenario 1 represented WINDS generated daily data series with the applied monthly changes from the year 2100 of the A1B climate change projection.

Scenario 2 – Climate change Scenario 2 was similar to Scenario 1 but with the applied A2 climate change projection. It represented the case when climate variables were affected the highest by future changes.

Scenario 3 – Climate change Scenario 3 was a modification of Scenario 1. Annual increases of temperature and precipitation for 2100 were applied uniformly for all months within a year as shown in table 1.

The generated 100 years of daily climate values were summarized for each month. Monthly average precipitation depths were calculated for each scenario run (fig. 3).

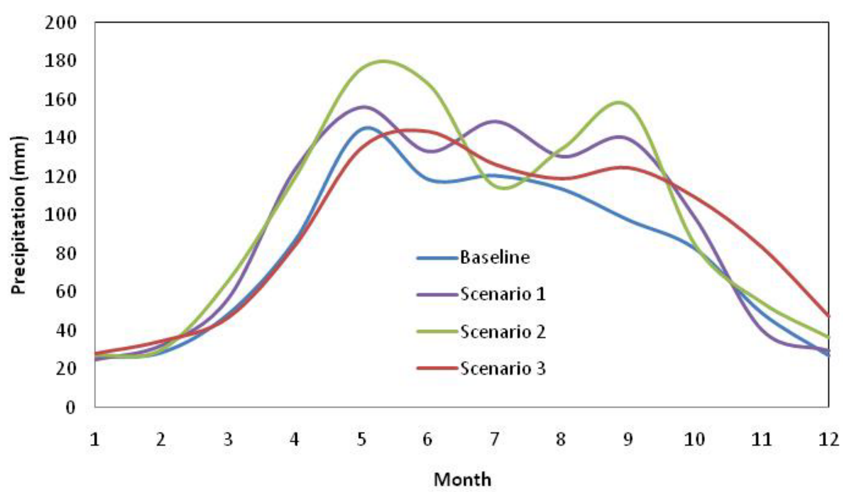

Figure 3. Monthly mean total precipitation depths for simulation scenarios.

METHODS

In order to further analyze the consequences of climate change in Kansas, this study used the Soil and Water Assessment Tool (SWAT) Model to simulate the generated climate change scenarios on an unregulated watershed in Kansas. The output of the SWAT model was then input into the Indicators of Hydrologic Alteration version 7.1 (IHA) software to calculate hydrologic indices for pre- and post- climate change. The hydrologic indices allowed climate change scenarios to be evaluated for aquatic ecosystems as well as terrestrial ecosystems. With these watershed scale evaluations, a better understanding of the effects of climate change can be achieved.

SWAT Model

The SWAT model is a physically based, continuous watershed scale model developed by the USDA Agricultural Research Service (SWAT 2005). This model was chosen because of the ability to model entire watersheds for a long period of time. The model inputs were gathered from various internet sources including the Kansas Geospatial Commons, the USDA Geospatial Data Gateway, as well as the NOAA National Climatic Data Center. The model inputs used for this study are as follows:

- Topography – 30 meter Digital Elevation Model (DEM)
- Landuse – NASS 2008 landuse layer
- Soil – STATSGO2 soil layer
- Climate Data – NCDC (calibration), NCAR GCM (climate simulation)
- Agricultural Data

The agricultural data used was for number of cattle per sub-basin. A weighted average of cattle population for each county based on total area of pasture/rangeland was used to determine the number of cattle per sub-basin. This data along with a continuous corn simulation were used as the baseline for the SWAT model.

Calibration

With the input information, SWAT was set up and calibrated using measured streamflow from the USGS gauging station at the watershed outlet. The major parameters that were modified during the calibration are presented in table 2. The calibration was performed for the years 1994 to 2000. Yearly and monthly streamflow calibrated very well with R^2 in the range of 0.85 to 0.93 and Nash-Sutcliffe in the range of 0.78 to 0.85. Daily streamflow also resulted in good calibration with R^2 of 0.56 and Nash-Sutcliffe of 0.52.

Table 2. SWAT Input Parameters

SWAT Parameter	Default Value or Range	Final Value or Factor
CN_2	69 – 87	Decrease by 5%
SURLAG	4	2
ESCO	0.95	0.8
EPCO	1.0	0.1

IHA Program

The IHA software is a statistical tool designed by The Nature Conservancy that is used to calculate the characteristics of natural and altered hydrologic data (IHA, 2009). IHA has two separate analysis options that are available. It can be used to calculate hydrologic indices over a continuous period of time, or to compare two separate time periods for evidence of hydrologic alteration. This program also has the option to calculate parametric or non-parametric statistics about the data. IHA was designed to work with streamflow measurements, but since it is a statistical program, different types of daily hydrologic data can be used like river stages, ground water levels or lake levels (IHA, 2009).

In order to compare the SWAT scenarios to the baseline scenario, the SWAT streamflow output of each scenario had to be placed in the same continuous time series with the baseline scenario. The IHA model was then used with a two period analysis to compare the selected hydrologic indices between the scenarios. The output of the IHA program provides an analysis of many hydrologic indices as well as flow duration curves. Only a few of the output indices were used to compare scenarios. The indices that were used along with the respective ecosystem influences from the IHA user's manual are presented in table 3.

Some slight adjustments were made to the IHA program in order to make the chosen hydrologic parameters more relevant to this study. The thresholds were adjusted for small floods (200 m^3/s) and large floods (350 m^3/s). These thresholds were calculated based on the data present in the baseline scenario. Also, during the low flow analysis, a seasonal water year of June 1st to August 31st was used so that only summer months were evaluated in the calculations.

Table 3. Hydrologic Indices Used

IHA Parameter Group	Hydrologic Parameters	Ecosystem Influences (IHA, 2009)
Magnitude of monthly water conditions	Mean flow for each calendar month	Habitat availability for aquatic organisms; Soil moisture availability for plants; Reliability of water supplies for terrestrial animals
Low flows	Low pulse count	Provide adequate habitat for aquatic organisms
	Low pulse duration	Maintain water table levels in floodplain, soil moisture for plants
Small Floods	Small flood peak	Recharge floodplain water table Deposit nutrients on floodplain
	Small flood duration	
	Small flood frequency	
Large Floods	Large flood peak Large flood duration Large flood frequency	Same as small floods
Flow Characteristics	Flow Duration Curve	

RESULTS

Mean monthly flow (fig. 4) was increased for all climate change scenarios when compared to the Baseline Scenario. The variation throughout the year was the more important aspect of these hydrologic indices. The scenarios showed a larger increase in mean monthly flows during the spring and fall months and a smaller increase during the summer and winter months. The uniform monthly shift in Scenario 3 did not show the same seasonal shifts as the other scenarios. This showed that the seasonal variation of climate change was lost with a uniform shift rather than the monthly shift used in Scenarios 1 and 2.

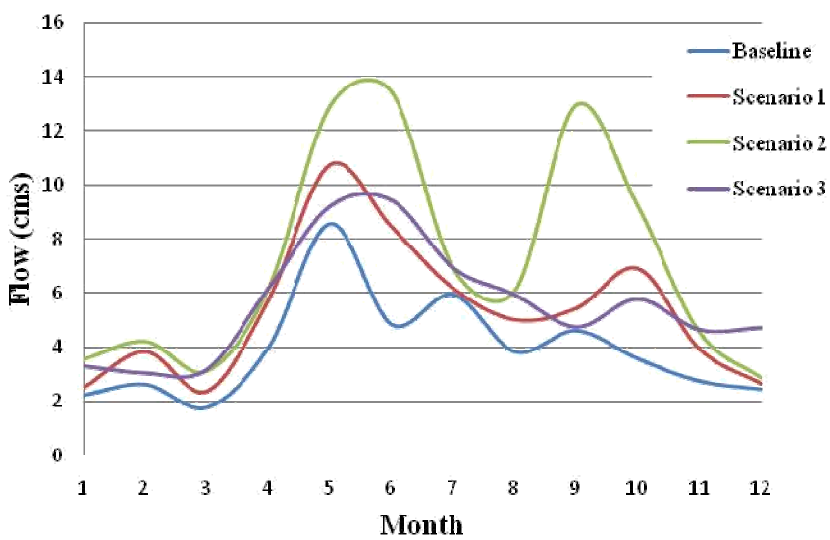

Figure 4. Mean Monthly Flows for baseline and three climate change scenarios

The other hydrologic indices computed in this study (table 4) illustrate similar patterns as figure 4. Scenario 1 shows that the frequency of small floods did not increase. However, the peak streamflow and duration of small floods was slightly increased. Frequency and duration of large floods decreased with this scenario, but peak discharge increased substantially. This demonstrated that even though the A1B scenario did not increase the number of floods, they will be larger and the high flows will last longer. This effect was caused by an increase in medium and large sized rain events. Another parameter that supports this cause was the low flow day index. The number and duration of low flow days were significantly reduced in Scenario 1.

Table 4. Indices of Hydrologic Alteration (IHA, 2009) Output summarized for four simulation scenarios

Hydrologic Parameter	Baseline	Scenario 1	Scenario 2	Scenario 3
Small Flood Peak (m^3/s)	261.1	264.6	235.7	264.3
Small Flood Duration (days)	55.25	62.88	77.58	45.35
Small Flood Frequency (times/yr)	0.4	0.4	0.65	0.6
Large Flood Peak (cms)	386.5	459.8	426.2	
Large Flood Duration (days)	51	40	94.67	
Large Flood Frequency (times/yr)	0.1	0.05	0.15	0
Large Flood Timing (Julian Date)	130, 139	302	161, 261, 229	
Low Pulse Count	1.8	0.9	0.45	1.05
Low Pulse Duration (days)	20.77	8.05	6.08	9.87

Scenario 2 showed slightly different results than Scenario 1. The small flood duration and frequency increased, but the peak streamflow decreased for Scenario 2. Large flood discharge, duration and frequency all increased in this scenario when compared to the baseline. This showed that the A2 climate scenario may lead to more floods that last longer, but have smaller magnitudes. Low flow indices were also reduced, showing that medium sized rainfall events also increased along with an increase in large events.

Comparing Scenarios 1 and 3 showed the difference in using monthly trends to simulate climate change compared to the yearly uniform trend that is commonly used. Scenarios 1 and 3 showed similar small flood peaks, but Scenario 3 showed a decrease in duration with an increase in frequency. This result was caused because the uniform shift in monthly precipitation caused some months to overestimate rainfall, while others to underestimate rainfall, causing less seasonal variation. Scenario 3 had no large flood events. Since the rest of the scenarios showed only three or fewer of these events for a 20-year period, the analysis period may need to be increased to improve accuracy when dealing with large flood events.

The flow duration curve (fig. 5) confirmed all of the data shown with the rest of the hydrologic indices. It showed an increase in the probability of larger flows compared to the baseline scenario. It also illustrated the reduction in low flow indices as the 100% flow was higher in the climate scenarios than the baseline.

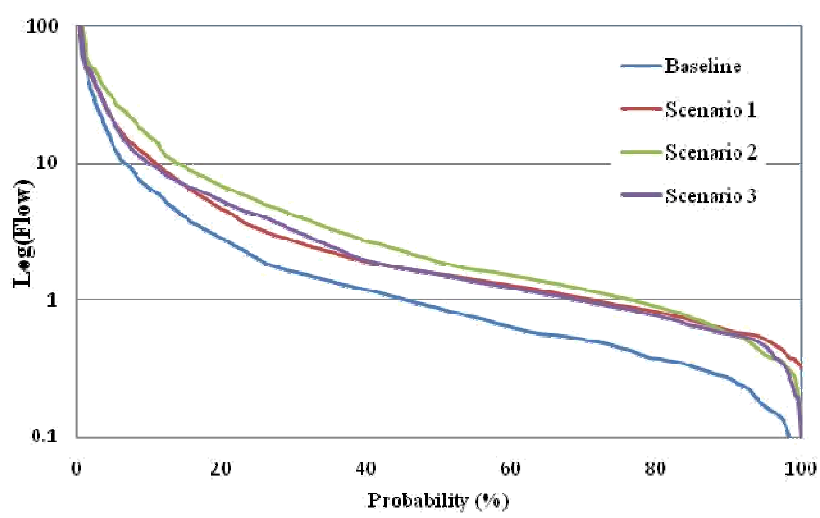

Figure 5. Flow Duration Curves

CONCLUSION

The impacts that climate change may have on a watershed scale cannot be fully understood with precipitation and temperature data alone. In this study, a method to temporally downscale GCM projections using monthly trends, NCDC weather data and a weather generator was developed. This method enables GCM trends to be simulated on a daily scale for input into SWAT. SWAT streamflow output was formatted and post-processed using the IHA program. The hydrologic output of this program was used to analyze the effects of climate change on water quantity.

The different climate simulations used in this study showed varying degrees of increase in monthly stream flow as well as an increase in either flood intensity or frequency. One important factor in climate change simulations were the seasonal shifts. Other studies in this area used a uniform yearly shift to simulate climate change. While this study did not show substantial differences when using a monthly shift, it was evident that seasonal shifts were lost with uniform climate change trends.

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