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# Trend and uncertainty analysis of simulated climate change impacts with multiple GCMs and emission scenarios

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ABSTRACT

Trends and uncertainty of the climate change impacts on hydrology, soil erosion, and wheat production during 2010–2039 at El Reno in central Oklahoma, USA, were evaluated for 12 climate change scenarios projected by four GCMs (CCSR/NIES, CGCM2, CSIRO-Mk2, and HadCM3) under three emissions scenarios (A2, B2, and GGa). Compared with the present climate, overall *t*-tests ($n = 12$) show that it is almost certain that mean precipitation will decline by some 6% (>98.5% probability), daily precipitation variance increase by 12% (>99%), and maximum and minimum temperature increase by 1.46 and 1.26 °C (>99%), respectively. Compared with the present climate under the same tillage systems, it is very likely (>90%) that evapotranpiration and long-term soil water storage will decease, but runoff and soil loss will increase despite the projected declines in precipitation. There will be no significant changes in wheat grain yield.

Paired *t*-tests show that daily precipitation variance projected under GGa is greater than those under A2 and B2 ($P = 0.1$), resulting in greater runoff and soil loss under GGa ($P = 0.1$). HadCM3 projected greater mean annual precipitation than CGCM2 and CSIRO ($P = 0.1$). Consequently, greater runoff, grain yield, transpiration, soil evaporation, and soil water storage were simulated for HadCM3 ($P = 0.1$). The inconsistency among GCMs and differential impact responses between emission scenarios underscore the necessity of using multi-GCMs and multi-emission scenarios for impact assessments. Overall results show that no-till and conservation tillage systems will need to be adopted for better soil and water conservation and environmental protection in the region during the next several decades.

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## 1. Introduction

The Global Climate Projections in the Fourth Assessment Report of "Climate Change 2007: The Physical Science Basis" prepared by the Intergovernmental Panel on Climate Change (IPCC, 2007) has concluded that global mean atmospheric temperature will likely increase between 1.8 and 4.0 °C by the end of this century, depending on the greenhouse gas (GHG) emissions scenarios. As a result of temperature rise, global hydrological cycles will intensify, and globally averaged mean water vapor, evaporation, and precipitation will likely increase in the century. Many General Circulation Models (GCMs) have consistently projected considerable increases in (1) the frequency and magnitude of extreme events including both droughts and heavy downpours during the century, (2) average daily rainfall intensity, especially for extreme rainfall events, and (3) spatial and temporal variability of precipitation (IPCC, 2007). The projected increases in the frequency and magnitude of extreme precipitation events are in line with the observed trends in many parts of the world. For example, across the contiguous United States, precipitation has increased by some 10% since 1910, and the increase has been primarily in the form of heavy and extreme daily storms (Karl and Knight, 1998). Specifically, about 53% of the total national increase is due to the precipitation increase within the upper 10% of all the daily precipitation amounts since 1910. Groisman et al. (2001) analyzed the trends in share of total annual precipitation occurring in heavy (>95th percentile), very heavy (>99th), and extreme daily precipitation events (>99.9th) in the contiguous U.S. between 1910–1970 and 1970–1999, and reported that the linear trends between the two periods increased by 4.6, 7.2, and 14.1% per decade, respectively, which are in contrast to the 1.2% increase per decade for total annual precipitation.

This projected increase towards more intense rainfall events is of great concern for assessing the potential impacts on surface hydrology, soil erosion, crop production, and environmental protection because severe soil erosion and catastrophic environ-

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mental destruction are often caused by infrequent heavy storms. A special report prepared by the Soil and Water Conservation Society in 2003 (SWCS, 2003) stated that under climate changes, the potential for such projected changes to increase the risk of soil erosion and related environmental consequences is clear, but the potential damage is not known and needs to be assessed. These insights are needed to determine (1) whether a change in soil and water conservation practices is warranted under changed climate and (2) what practices should be taken to adequately protect soil and water resources if a change is warranted. Therefore, proper assessment of potential impacts of climate change is critical to developing strategic plans and adaptations to mitigate the adverse effects and protect ecosystems and environments.

Mismatches in time and space between GCM resolution and input requirements of hydrological and crop models are major challenges for impact assessment. Both dynamic and statistical downscaling methods have been used to couple GCM output and simulation models. Using various statistical downscaling methods, many researchers have coupled GCM projections with hydrological and agricultural systems models and evaluated the potential impacts of projected climate changes on crop productivity (e.g., Rosenzweig and Parry, 1994; Semenov and Porter, 1995; Mearns et al., 1997; Mavromatis and Jones, 1998), and on surface runoff and soil erosion (e.g., Favis-Mortlock et al., 1991; Boardman and Favis-Mortlock, 1993; Favis-Mortlock and Savabi, 1996; Pruski and Nearing, 2002a,b; Zhang et al., 2009). General results indicated that surface runoff and soil erosion would very likely increase as rainfall intensity increases under climate change. The rates of the increases are directly linked to the frequency and intensity of extreme precipitation events (Pruski and Nearing, 2002a; Zhang et al., 2009). In recent years, the Water Erosion Prediction Project (WEPP) model has been used to simulate the potential impacts of climate change on soil erosion and surface runoff in U.S. (e.g., Pruski and Nearing, 2002a,b; O'Neal et al., 2005; Zhang and Nearing, 2005), Belgium (Nearing et al., 2005), U.K. (Favis-Mortlock and Savabi, 1996; Mullan and Favis-Mortlock, 2010), Austria (Klik and Eitzinger, 2010), South Korea (Kim et al., 2009), and China (Zhang et al., 2009; Li et al., 2010).

Proper spatial and temporal treatments of climate variation and change during downscaling are crucial for yielding reliable impact assessment. Zhang (2005) developed a statistical downscaling method that treats spatial and temporal climate variation explicitly by using transfer functions for spatial downscaling and a stochastic weather generator for temporal downscaling. Compared with the conventional downscaling approaches, this method tends to produce greater surface runoff and soil erosion due to more detailed treatment of spatiotemporal climate variation (Zhang, 2007). It has been used to study the impact of climate change at particular locations on rainfall erosivity (Zhang et al., 2010) and soil hydrology and soil erosion (Zhang et al., 2009; Li et al., 2010).

The objective of this work is to quantify trends and uncertainties of climate change and its impacts on runoff, soil water, soil erosion, and wheat production at a unit watershed near El Reno, Oklahoma, USA, during 2010–2039. The climate change scenarios, projected by four GCMs under three GHG emission scenarios, were downscaled to the target location using an explicit spatiotemporal downscaling method of Zhang (2005).

## 2. Materials and methods

### 2.1. Watershed description

Three experimental watersheds, located at the Grazinglands Research Laboratory, 7 km west of El Reno, Oklahoma were used in the WEPP model calibration and for future climatic impact simulation. Each watershed is 80 m wide and 200 m long with a drainage area of 1.6 ha. The longitudinal slope of the watershed is approximately 3 to 5%. Soils are primarily silt loam with an average of 23% sand and 56% silt in the tillage layer. The climate at the location is characterized as semiarid to subhumid with large seasonal and interannual precipitation variability. The mean monthly precipitation is bimodal with the primary peak in May–June and the secondary peak in August–October. A common regional cropping system (annual winter wheat–summer fallow) with three contrasting tillage systems of no-till, conservation (disks) and conventional (moldboard) tillage systems was primarily studied on each watershed between 1980 and 1996. Measured weather data, soil properties, wheat yield, surface runoff and soil loss were used to calibrate the plant growth, effective hydraulic conductivity, and soil erosion components of the WEPP model in a sequential and iterative manner (Zhang, 2004; Zhang and Nearing, 2005).

### 2.2. WEPP model and calibration

The WEPP model (version 2010.1), which is a process-based, continuous daily simulation model (Flanagan and Nearing, 1995), simulates soil erosion, hydrological processes, daily water balance, plant growth, and residue decomposition components. For simulating the impacts of climate change, the plant growth and water balance components in the WEPP model were modified to account for the $CO_2$ effects on evapotranspiration (ET) and biomass production as is used in the APEX models (Williams et al., 2008). The WEPP model simulates eventual, monthly, and annual soil loss and runoff from a hillslope or small watershed. It uses four input files including soil, topography, climate, and crop management. It also includes a climate generator (CLIGEN), which generates daily rainfall pattern, daily temperature (maximum, minimum, and dew point), solar radiation, and wind speed and direction (Nicks and Gander, 1994). Precipitation occurrence is generated using a first-order, two-state Markov chain based on conditional transition probabilities of a wet day following a wet day ($P_{w/w}$) and a wet day following a dry day ($P_{w/d}$). Daily precipitation amounts are generated using a skewed normal distribution, and daily temperature and radiation are generated using normal distributions. CLIGEN was evaluated for the study region at four weather stations across Oklahoma (Zhang and Garbrecht, 2003). The mean absolute relative errors were 4.7 and 1.7% for simulating means of daily and monthly precipitation amounts, respectively, and 3.7 and 6.7% for simulating standard deviations.

The key WEPP parameters calibrated here included effective hydraulic conductivity for runoff prediction, harvest index and energy-biomass conversion ratio for biomass and grain yields, and interrill and rill erodibilities for soil loss. Remaining parameters retained the model's default values. Since the physiographic conditions of the three watersheds were similar, only one set of these parameters was calibrated, which were 7.95 mm/h for effective saturated hydraulic conductivity, 0.26 for harvest index, 23 g/kJ for energy–biomass ratio, $1 \times 10^6$ kg s/m$^4$ for interrill erodibility, 0.0035 s/m for rill erodibility, and 6.3 Pa for critical shear stress. These calibrated soil erodibility parameter values are well within the ranges recommended based on soil properties by the model. More information on the parameter calibration can be found in Zhang (2004) and Zhang and Nearing (2005).

### 2.3. GCMs and emissions scenario

Four GCMs (CCSR/NIES, CGCM2, CSIRO-Mk2, and HadCM3) and three emissions scenarios (A2, B2 and GGa) from the Third Assessment Report (IPCC, 2001) were used, and the respective spatial resolutions of the four GCMs were 5.625° (long.) × 5.625° (lat.), 3.75° × 3.75°, 5.625° × 3.25°, and 3.75° × 2.5°. The three emissions