Climatic Change (2017) 140:259–272
DOI 10.1007/s10584-016-1850-7

Impact of air pollution induced climate change on water availability and ecosystem productivity in the conterminous United States

Kai Duan[1] · Ge Sun[2] · Yang Zhang[1] · Khairunnisa Yahya[1] · Kai Wang[1] · James M. Madden[1] · Peter V. Caldwell[3] · Erika C. Cohen[2] · Steven G. McNulty[2]

Received: 19 July 2016 / Accepted: 29 October 2016 / Published online: 8 November 2016

Abstract Air pollution from greenhouse gases and atmospheric aerosols are the major driving force of climate change that directly alters the terrestrial hydrological cycle and ecosystem functions. However, most current Global Climate Models (GCMs) use prescribed chemical concentrations of limited species; they do not explicitly simulate the time-varying concentrations of trace gases and aerosols and their impacts on climate change. This study investigates the individual and combined impacts of climate change and air pollution on water availability and ecosystem productivity over the conterminous US (CONUS). An ecohydrological model is driven by multiple regional climate scenarios with and without taking into account the impacts of air pollutants on the climate system. The results indicate that regional chemistry-climate feedbacks may largely offset the future warming and wetting trends predicted by GCMs without considering air pollution at the CONUS scale. Consequently, the interactions of air pollution and climate change are expected to significantly reduce water availability by the middle of twenty-first century. On the other hand, the combined impact of climate change and air pollution on ecosystem productivity is less pronounced, but there may still be notable declines in eastern and central regions. The results suggest that air pollution could aggravate

Electronic supplementary material The online version of this article (doi:10.1007/s10584-016-1850-7) contains supplementary material, which is available to authorized users.

✉ Ge Sun
gesun@fs.fed.us

✉ Yang Zhang
yzhang9@ncsu.edu

[1] Department of Marine, Earth, and Atmospheric Sciences, North Carolina State University, Raleigh, NC, USA

[2] Eastern Forest Environmental Threat Assessment Center, USDA Forest Service, Raleigh, NC, USA

[3] Coweeta Hydrologic Laboratory, USDA Forest Service, Otto, NC, USA

regional climate change impacts on water shortage. We conclude that air pollution plays an important role in affecting climate and thus ecohydrological processes. Overlooking the impact of air pollution may cause evident overestimation of future water availability and ecosystem productivity.

Keywords Air pollution · Climate change · Water availability · Ecosystem productivity

1 Introduction

Water and carbon cycles are tightly linked at broad scales in the terrestrial ecosystem (Noormets et al. 2008; Sun et al. 2011). Precipitation is partitioned into change in soil water storage, evapotranspiration (ET), and runoff (i.e., water yield) in the hydrologic system. Soil moisture and ET directly affect photosynthesis and act as one of the major controls of carbon uptake and ecosystem productivity. Water consumption by plants has a considerable feedback to water cycles that alters the water budget through the processes of canopy interception and plant transpiration. The extensive impacts of greenhouse gas (GHG) emissions on climate change and associated influences on water-carbon components have been recognized, ranging from ET and runoff to gross ecosystem productivity (GEP) and net ecosystem exchange (NEE) (Ahlström et al. 2012; Duan and Mei 2014a; Duan et al. 2016a; Ge et al. 2013; Keenan et al. 2013; Thompson et al. 2014).

Air pollution is another important factor that affects regional climate and water-carbon cycles (Ramanathan et al. 2001, 2005). Atmospheric aerosols released by human activities can alter the radiative balance between the atmosphere and earth surface by enhancing the scattering and absorption of solar radiation, which leads to a reduction in solar irradiance and a corresponding drop of temperature near the land surface (Huang et al. 2006). Also, aerosols act as cloud condensation nuclei (CCN) and ice nuclei (IN) in atmosphere dynamics, and thus can affect cloud properties and the initiation of rain and snow (Givati and Rosenfeld 2004; Tao et al. 2012; Zhang 2008; Zhang et al. 2010, 2015a, 2015b). Due to various atmospheric backgrounds and cloud types, aerosols may either increase or decrease the formation of precipitation based on different radiative and nuclei activities (Khain et al. 2008; Rosenfeld et al. 2008). Moreover, air pollutants and GHGs may interact physically and chemically in the atmosphere and make it more challenging to project the future variations in climate (Bytnerowicz et al. 2007).

Simulation tools are required to link the atmospheric dynamics with ecohydrological processes to predict how climatic perturbations will affect regional ecohydrology. Numerous climate downscaling techniques have been developed to scale GCM projections to a spatial scale that is relevant to ecohydrological processes. In general, there are two kinds of downscaling approaches, known as dynamical downscaling and statistical downscaling, using atmospheric physics principles and empirical statistics, respectively. Statistical models have been widely adopted for their efficiency and flexibility. However, these models cannot reflect the possible changes in the statistical relationships between predictors and predictands in the future due to the absence of physical mechanisms (Duan and Mei 2014b; Wood et al. 2004). On the other hand, Regional Climate Models (RCMs) that downscale GCMs dynamically are increasingly used by ecohydrological modelers for their merits in capturing multi-variable atmospheric interactions (Kay et al. 2015; Wang et al. 2015a). Benefitting from the growing computational power, a number of RCMs with coupled meteorology-air quality modules have been introduced to address the processes of meteorology and chemistry interactions, such as chemistry-aerosol-radiation-cloud-precipitation-climate interactions (Forkel et al. 2015; Zhang 2008; Zhang et al. 2010, 2012a, 2012b, 2015a, 2015b). The development of these advanced RCMs makes it possible to recognize the impacts of interactions between chemical species (e.g., GHGs and short-lived pollutants) and climate systems, which are highly complicated and uncertain and involve a range of meteorological and chemical variables.

This study assesses the individual and combined impacts of climate change and air pollution on the water and carbon cycles over the conterminous U.S. (CONUS). Within a top-down simulation framework, we have linked a GCM (the North Carolina State University's version of the Community Earth System Model, referred to as CESM-NCSU) (Gantt et al. 2014; He and Zhang 2014; He et al. 2015a, 2015b), an RCM (the Weather Research and Forecasting model with Chemistry, WRF/Chem) (Grell et al. 2005; Wang et al. 2015b), and an ecohydrological model (the Water Supply Stress Index model, WaSSI) (Caldwell et al. 2012; Sun et al. 2011) to examine the ecohydrological responses to multiple climate scenarios with and without taking into account the impacts of air pollution on climate.

2 Methods

2.1 Study area

The CONUS consists of the 48 adjoining states and Washington D.C. of the U.S. (Fig. 1). In the national hierarchical system of hydrologic units defined by the United States Geological Survey (USGS), CONUS covers 18 water resources regions (WRR) at the first level (2-digit units), or approximately 82,773 12-digit Hydrologic Unit Code (HUC-12) watersheds at the sixth level (USGS and USDA 2013). There are 1073 ~ 13,455 HUC-12 watersheds nested within each WRR and span a large climatic gradient (see Supplementary Table S1). The observed climate data (2001–2010) derived from the Parameter-elevation Relationships on

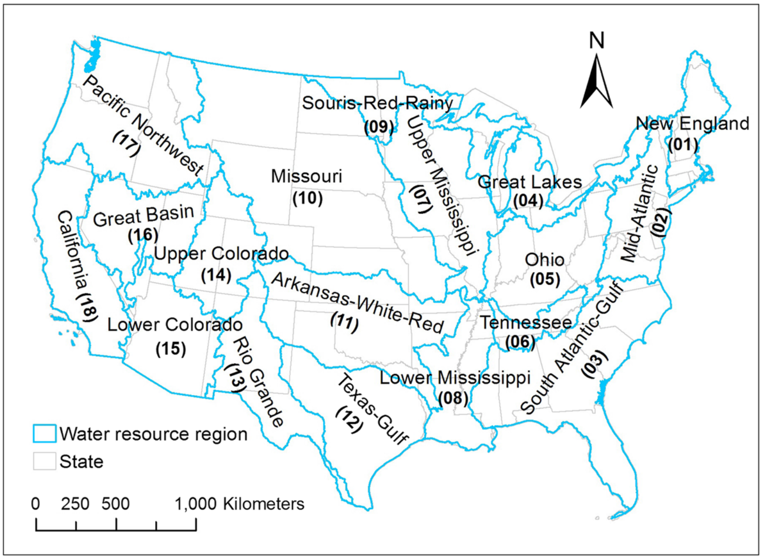


Fig. 1 Distributions of the 18 water resource regions (WRRs) over the CONUS

Independent Slopes Model (PRISM) datasets (Daly et al. 2008) show a clear latitudinal rise of near surface temperature from south to north between 4 °C and 19 °C. The multi-year mean annual precipitation ranges from 295 mm $yr.^{-1}$ (Lower Colorado, WRR15) to 1371 mm $yr.^{-1}$ (Lower Mississippi, WRR8) among the WRRs. The driest regions with precipitation less than 400 mm $yr.^{-1}$ cover WRR13 ~ 16 in the southwest.

2.2 Models

The integrated atmosphere-hydrosphere model system developed in this work consists of three component models. Each of them is described briefly below.

2.2.1 Global climate model

Global earth system projections used in this study are from CESM-NCSU (Gantt et al. 2014; He and Zhang 2014; He et al. 2015a, 2015b). The original CESM was developed by the National Center for Atmospheric Research (NCAR) to investigate diverse earth system interactions between atmosphere, ocean and land at multiple temporal and spatial scales (Hurrell et al. 2013). As one of the state-of-art earth system models, CESM includes a number of modules to describe atmosphere transport and chemistry, carbon-nitrogen cycling, marine ecosystem biogeochemistry, and anthropogenic activities by coupling the physical climate system with biology, chemistry, biogeochemistry, and social systems. A large number of CESM simulations with different configurations have contributed to the fifth phase of the Coupled Model Intercomparison Project (CMIP5) and the Fifth Assessment Report (AR5) of IPCC (Taylor et al. 2012). Although a chemistry module has been incorporated into the standard versions of CESM released by NCAR, it simulates highly simplified gas-phase chemistry and aerosol processes. The CESM-NCSU is an updated version of CESMv1.2.2/CAM5.3 with advanced gas-phase chemistry, inorganic and organic aerosol treatments, and aerosol-cloud interactions. Multiple decadal simulations have been performed at a horizontal resolution of 0.9° × 1.25° and a vertical resolution of 30 layers. The comprehensive model evaluations have shown that the performance of CESM-NCSU in reproducing the current climate and air quality is consistent with or even better than that of other climate models. The advanced treatments along with comprehensive model evaluations can be found in details elsewhere (Gantt et al. 2014; He and Zhang 2014; He et al. 2015a, 2015b).

2.2.2 Regional climate model

The regional climate models used in this study include the officially released Weather Research and Forecasting model (WRF) version 3.6.1 by NCAR (Skamarock et al. 2005) and the NCSU version of WRF/Chem, version 3.6.1 (Wang et al. 2015b; Yahya et al. 2016). Both WRF and WRF/Chem include the same background concentrations of CO_2, CH_4, and N_2O under current and future climate scenarios. Compared to the WRF model or most other traditional regional climate models, WRF/Chem considers dynamic feedbacks between air pollutants (e.g., trace gases and aerosols) and meteorology/climate, and thus allows for investigating the complex chemistry-aerosol-radiation-cloud-precipitation-climate interactions. The major modifications in the NCSU version of the WRF/Chem model include the implementation of a widely used gas-phase chemical mechanism, i.e., the 2005 version of Carbon Bond mechanism (CB05) with the chlorine chemistry and its coupling with the Modal Aerosol

Dynamics for Europe/Volatility Basis Set (MADE/VBS) aerosol module. The MADE/VBS aerosol module uses the modal aerosol size distribution and includes the advanced secondary organic aerosol treatment. The chemical option CB05-MADE/VBS is linked with existing model treatments for various chemistry-aerosol-radiation-cloud-precipitation feedback processes in WRF/Chem. These processes include the direct effect of aerosol particles on short- and long wave radiation, the aerosol semi-direct effects on photolysis rates of major gaseous pollutants, the aerosol indirect effects (including both the first and second indirect effects) on cloud formation and lifetime through changing cloud albedo, droplet number concentration, and droplet radius. Other improvements include the implementation of sulfur dioxide heterogeneous chemistry and updates on cloud chemistry with both treatments being able to improve predicted aerosol concentrations. In this study, WRF and WRF/Chem simulations are conducted at a horizontal resolution of 36 × 36 km (148 × 112 grids over the CONUS) and a vertical resolution of 34 layers from near surface to 100 mb. More details can be found in the literature (Wang et al. 2015b; Yahya et al. 2016).

2.2.3 Ecohydrological model

The ecohydrological processes are simulated with a previously validated monthly Water Supply Stress Index model (WaSSI) that estimates water and carbon cycles by biome at HUC-12 watershed scale (Sun et al. 2015b). WaSSI describes water (i.e., ET, soil moisture, runoff) and carbon (i.e., GEP; respiration; NEE) balances by a set of submodels that have been well validated with site-level streamflow measurements, regional remote sensing ET data, and eddy flux monitoring of FLUXNET across the US (Caldwell et al. 2012; Sun et al. 2011). The model uses a conceptual snow submodel to divide precipitation into snowfall and rainfall based on the mean elevation and air temperature in the watershed, and to compute snow melt/accumulation and snow water equivalent. The core of WaSSI is the ecosystem ET model that estimates ET through its empirical relationships with precipitation, Hamon potential evapotranspiration (PET), and leaf area index (LAI). These equations are established independently for 10 different types of land cover, including cropland, deciduous forest, evergreen forest, mixed forest, grassland, shrubland, wetland, open water, urban area, and barren land. Then, the actual ET is computed by constraining this estimate with soil water availability simulated by the Sacramento Soil Moisture Accounting model (SAC-SMA) (Burnash 1995), accompanied by the hydrologic processes of infiltration, soil water movement and runoff generation. The carbon balance in the ecosystem is modeled by linear correlations between monthly GEP and ET (Water Use Efficiency, WUE) for each plant functional type. Respiration (Re) is calculated as a suite of regression functions of GEP, and NEE is further simulated as the difference between Re and GEP (NEE = Re − GEP).

2.3 Modeling experiments

The overall procedures of coupling CESM-NCSU, WRF/Chem, and WaSSI are as follows. First, the decadal global climate simulations are performed using CESM-NCSU under the Representative Concentration Pathway (RCP) 4.5 and RCP8.5 scenarios. While RCP8.5 represents a fossil fuel intensive emission scenario, RCP4.5 represents low-to-medium emission scenario with carbon policies. Second, the decadal regional climate simulations are performed using either WRF or WRF/Chem models with initial and boundary conditions derived from CESM-NCSU outputs and bias-corrected against the National Centers for Environmental

Prediction (NCEP) reanalysis data. Third, the raw hourly outputs of climate data (i.e., surface air temperature and precipitation) from WRF or WRF/Chem simulations are extracted across the CONUS domain and averaged on a monthly basis, and then the monthly climate data are bias-corrected toward the PRISM dataset using the Bias Correction and Spatial Disaggregation method (BCSD) (Werner and Cannon 2015; Wood et al. 2002, 2004). Finally, the bias-corrected precipitation and temperature series are scaled to HUC-12 watersheds and used to drive the WaSSI model for reproducing ecohydrological processes. The water balance (precipitation, ET, runoff) and carbon balance (GEP, Re, NEE) components of interest are calculated independently for each land cover type within each watershed at monthly scale, and then the area-weighted aggregations in HUC-12 watersheds, WRRs and the entire CONUS can be acquired.

To examine the impacts of climate change only and combined impacts of both climate and air quality changes by considering the air quality-climate feedbacks, four climate scenarios are developed with different emission levels and chemistry-climate feedback options, including the WRF simulations under RCP4.5 and RCP8.5 (referred to as W/4.5 and W/8.5, respectively), and the WRF/Chem simulations under RCP 4.5 and RCP8.5 (referred to as WC/4.5 and WC/4.5, respectively). The main difference between WRF and WRF/Chem simulations lies in the fact that dynamic chemistry-climate feedbacks caused by time-varying concentrations of chemical species are accounted for in WRF/Chem but not in WRF (which only includes prescribed concentrations of GHGs). The changes in climate variables from the baseline period 2001–2010 to the future period 2046–2055 are investigated to interpret the potential effects of GHGs and air pollution on future climate and ecohydrology.

3 Results

3.1 Projected changes in regional climate

The regional mean annual temperature (Fig. 2a) is projected to increase by 0.9 ~ 1.3 °C (W/4.5), 0.5 ~ 1.1 °C (WC/4.5), 1.1 ~ 1.6 °C (W/8.5), and 0.9 ~ 1.5 °C (WC/8.5) under the four scenarios, with the CONUS average reaching 1.1, 0.8, 1.3, and 1.1 °C, respectively. W/8.5 is the warmest scenario in all the 18 regions, followed by WC/8.5, W/4.5, and then WC/4.5. The discrepancy between WC/4.5 & W/4.5 and WC/8.5 & W/8.5 suggests that air pollution is expected to largely offset the warming effects of GHGs. However, there will still be notable temperature increases under the combined impact of GHGs and air pollution. Across the regions, larger increases are expected to occur in the upper midwest (WRR9 ~ 10) and western (WRR14 ~ 18) regions. Note that the regional differences in temperature rise are obviously larger under the two WRF/Chem scenarios (WC/4.5 and WC/8.5). Air pollution may impose a larger cooling effect in the eastern (WRR2 ~ 8) and southern (WRR11 ~ 13) regions.

The precipitation projections (Fig. 2b) suggest diverse trends among the regions. Precipitation is expected to increase nationwide under the two WRF scenarios (W/4.5 and W/8.5), up to 21 % and 18 % in WRR18 (California). The exception can be mainly found in the central U.S. (WRR9 ~ 11) with a decrease up to 7 %. The projections under WC/4.5 and WC/8.5, on the other hand, show extensive decreases in precipitation ranging from WRR1 (New England) to WRR14 (Upper Colorado) (exceptional cases can be found in WRR3,4,8,12). A much drier atmosphere is projected under WC/4.5, with the most severe decrease reaching 18 % in WRR6 (Tennessee). However, the four scenarios consistently suggest an increasing trend of precipitation in the western regions WRR15 ~ 18, varying between 5 % ~ 20 %.

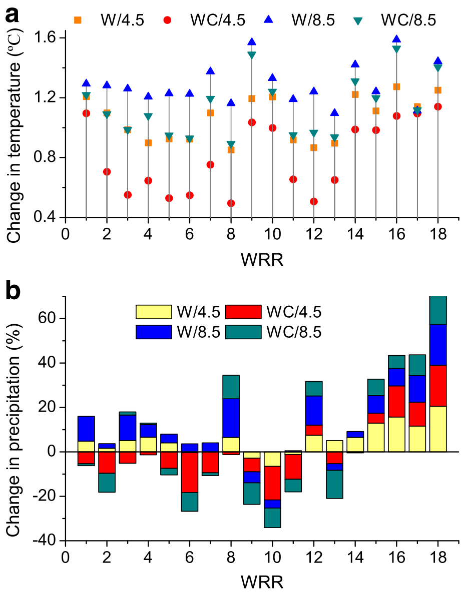


Fig. 2 Changes in mean annual temperature (**a**) and precipitation (**b**) in the 18 WRRs from the baseline (2001–2010) to future (2046–2055) periods under the four climate scenarios

3.2 Impacts on runoff and GEP

The changing temperature and precipitation will lead to significant decrease in future runoff in most regions (Fig. 3a). Consistent with the evident decrease in precipitation in WRR6 ~ 7, 9 ~ 11, and 13, a severe decline in runoff (up to 45 %) is expected to occur in these regions. The exceptional cases are WRR12, 17, and 18, where an increase is expected under all the scenarios.

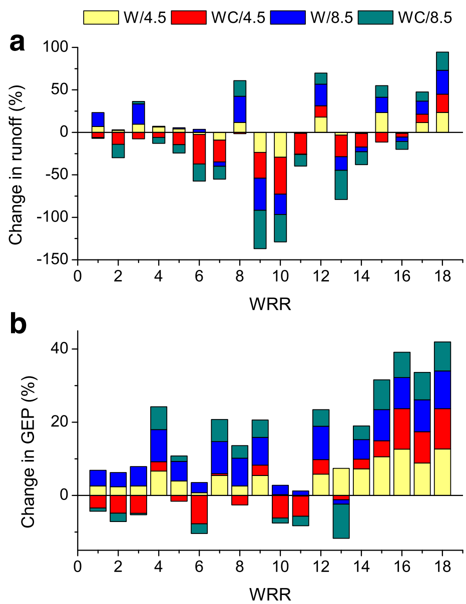


Fig. 3 Changes in mean annual runoff (**a**) and GEP (**b**) in the 18 WRRs from the baseline (2001–2010) to future (2046–2055) periods under the four climate scenarios

Larger regional diversity in runoff change can be observed across the HUC-12 watersheds (Fig. 4). Increases are mainly found in areas adjacent to the Pacific coast (WRR15, 17, 18) and Gulf of Mexico (WRR3, 8, 12), ranging from near zero to over 100 %. Conversely, annual runoff is projected to drop dramatically by over 50 % in most watersheds across the central (WRR10 ~ 11) and southwestern (WRR13) CONUS. Among the four scenarios, W/4.5 (Fig. 4a) and W/8.5 (Fig. 4c) generally suggest a stronger signal of increasing runoff, while WC/4.5 (Fig. 4b) and WC/8.5 (Fig. 4d) suggest much drier conditions. It is worth noting that runoff decrease is expected to cover a greater area when chemistry-climate feedbacks are accounted for, especially in the east (WC scenario).

Due to the increases in both temperature and precipitation in the western regions WRR14 ~ 18 (Fig. 2), regional averaged GEP is projected to increase by 3 % ~ 13 % in all of the four scenarios (Fig. 3b). Similar consistent increase is also projected in WRR4, 7, 9, and 12. In the other regions, particularly the Atlantic coast (WRR1–3) and central (WRR10, 11, 13) CONUS, the scenarios with or without chemistry-climate feedbacks generally show opposite changing directions in GEP, i.e., increase under W/4.5 and W/8.5, and decrease under WC/4.5 and WC/8.5. At watershed level (Fig. 5), the highest increases in GEP reach 50 % ~ 100 % in a number of arid watersheds in the south of California and Texas, while the most severe decrease (up to 35 %) is projected in the central regions (WRR10, 11, 13).

3.3 Changes in overall water-carbon cycle

We examined the overall changes in the key water-carbon components (Fig. 6) to explore the impact of GHGs and air pollution on the large-scale ecohydrological cycle over the CONUS. The projections under W/4.5 and W/8.5 scenarios suggest increasing temperature and precipitation with the influence of GHGs emission, which tend to enhance both water and carbon fluxes. In this case, precipitation, ET, and runoff are projected to increase by 32 (4 %), 22

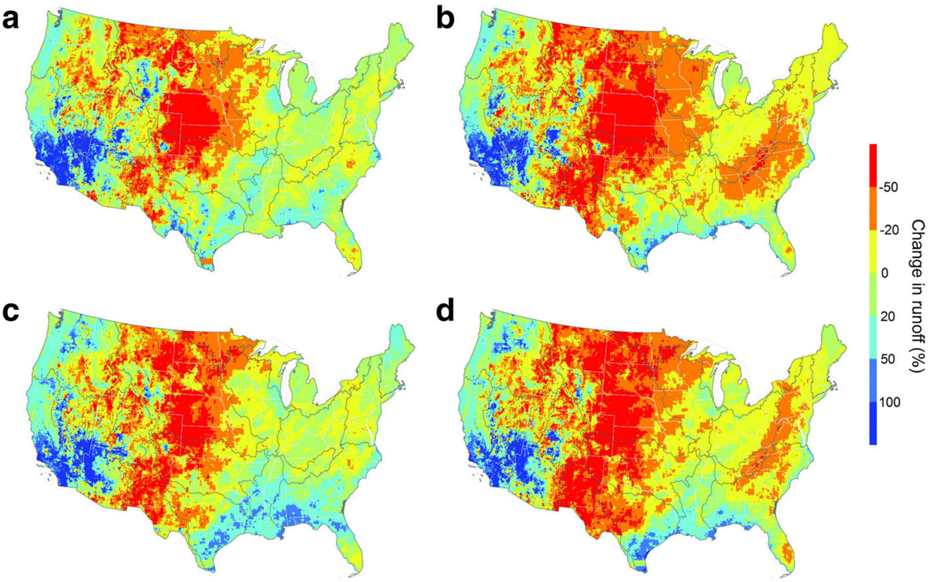


Fig. 4 Changes in mean annual runoff across the watersheds from the baseline (2001–2010) to future (2046–2055) periods under the W/4.5 (**a**), WC/4.5 (**b**), W/8.5 (**c**), and WC/8.5 (**d**) scenarios

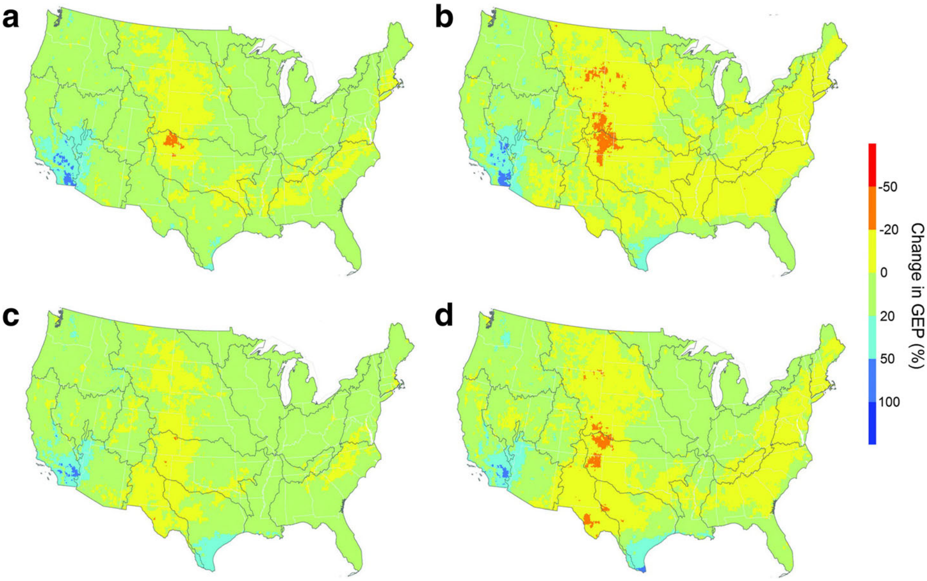
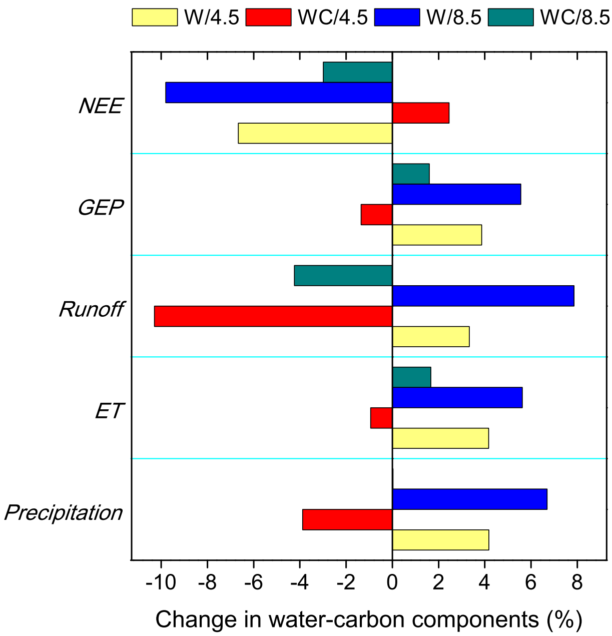


Fig. 5 Changes in mean annual GEP across the watersheds from the baseline (2001–2010) to future (2046–2055) periods under the W/4.5 (**a**), WC/4.5 (**b**), W/8.5 (**c**), and WC/8.5 (**d**) scenarios

(4 %), and 9 (3 %) mm yr.$^{-1}$ under W/4.5, and by 52 (7 %), 29 (6 %), and 21 (8 %) mm yr.$^{-1}$ under W/8.5, respectively. At the same time, GEP is also projected to increase by 48 (4 %) and 69 (6 %) g C m^{-2} yr.$^{-1}$. With the rise of GEP, the changes in NEE reach −23 (−7 %) and −34 (−10 %) g C m^{-2} yr.$^{-1}$ in W/4.5 and W/8.5 scenarios, indicating more carbon sequestered from the atmosphere to the ecosystem (i.e., larger carbon sink strength).

Fig. 6 Summary of the mean annual changes (%) in water-carbon components over the entire CONUS from the baseline (2001–2010) to future (2046–2055) periods



WC/4.5 and WC/8.5 represent the climate change scenarios induced by both GHGs and air pollution. Compounded with the negative effects of chemistry-aerosol interactions, temperature will still rise by 0.8 and 1.1 °C, but precipitation is projected to decrease by −30 (−4 %) mm $yr.^{-1}$ under WC/4.5 and stay nearly unchanged under WC/8.5. Driven by such changes in temperature and precipitation, ET and GEP will decrease by −5 mm $yr.^{-1}$ (−1 %) and −17 g C m^{-2} $yr.^{-1}$ (−1 %) under WC/4.5, butincrease by 9 (2 %) mm $yr.^{-1}$ and 20 (2 %) g C m^{-2} $yr.^{-1}$ under WC/8.5, while NEE is projected to change by 8 (2 %) and-10 (−3 %) g C m^{-2} $yr.^{-1}$ in the two scenarios. Most notably, runoff is expected to decrease significantly by −27 (−10 %) and −11 (−4 %) mm $yr.^{-1}$ under WC/4.5 and WC/8.5, respectively.

4 Summary and discussion

This study investigates watershed ecohydrological responses to regional climate variations induced by two major anthropogenic factors — GHGs emission and air pollution. The results suggest that GHGs and air pollution tend to drive air temperature and precipitation toward opposite changing directions. Under the individual impact of GHGs emission, CESM-NCSU agrees with most of the CMIP5's GCMs on the generally warmer and wetter future over the CONUS (Duan et al. 2016b; Greve et al. 2014). However, air pollution is expected to partially offset the warming and wetting trends to different degrees. Air pollutants may cool down the temperature by 0.2 ~ 0.3 °C at CONUS scale and 0.1 ~ 0.4 °C at regional scale, but GHG concentrations will still be the dominating driver of temperature change. For precipitation, air pollution's negative effect is projected to counterbalance the GHGs' positive effect to a larger degree, which will cause an overall decrease of −30 mm $yr.^{-1}$ (−4 %) under RCP4.5, and nearly no change under RCP8.5.

Potential changes in temperature and precipitation will alter the moisture and energy supplies to ecohydrological processes, and thus water and carbon fluxes between atmosphere and surface. Under the individual effect of GHGs (Fig. S1a), the combinations of increasing temperature and precipitation will enhance ET, runoff, and GEP. In contrast, air pollution caused by short-lived trace gases and aerosol (Fig. S1b) tends to suppress water and carbon cycles and leads to decline in both runoff and GEP. Note that we did not specifically quantify the individual effect of air pollution in this study. However, the differences between the simulations based on WRF/Chem and WRF scenarios implicitly reveal the impact of air pollution and its interactions with GHGs on water-carbon cycles.

The combined impact of GHGs and air pollution (Fig. S1c) may lead to different changing directions of precipitation and ET under different emission scenarios, namely decrease under RCP4.5 and increase under RCP8.5. Commensurate decrease and increase in GEP are expected under RCP4.5 and under RCP8.5, respectively. Although the overall change in GEP is minimal (within ±2 %), there is a significant reduction in the eastern regions. Meanwhile, the integrated impact is expected to cause a notable reduction in runoff under either scenario (−10 % under RCP4.5 and −4 % under RCP8.5), especially in central and southwestern U.S.

In summary, our results suggest that the interactions of air pollution and climate change are likely to significantly suppress water availability by the middle of the twenty-first century. On the other hand, the combined impact on ecosystem productivity is less significant, but a notable decline may still occur in eastern and central regions.

We here focus on evaluating the impact of climate variability induced by GHGs and air pollution. However, future changes in water availability and ecosystem productivity, especially at the local scale, may also be largely disturbed by other environmental factors such as radiation (Gedney et al. 2014), urbanization and deforestation (Sun et al. 2015a), and direct effects of GHGs and pollutants on plant transpiration (Cheng et al. 2014; Gedney et al. 2006; Rudd and Kay 2015; Pan et al. 2015). For instance, while ozone pollution is expected to reduce plant growth, there is evidence that air pollution in the form of carbon and nitrogen can fertilize the growth of young forests in the southern U.S. (Tian et al. 2012), despite the decreased water and energy supplies caused by pollutants.

Also, our selection of models may introduce uncertainties into the results. This study uses a one-way coupling scheme to connect the ecohydrological model to the climate models. The dynamic interactions between vegetation and atmosphere (Krinner et al. 2005) were not considered at watershed scale. We limited our analysis to the results from one GCM, one RCM, and one ecohydrological model, while other models with different focuses may lead to inconsistency on global and regional climate projections and water-carbon processes to various degrees. For example, the estimation of GEP in WaSSI model is based on the assumptions of water-carbon coupling and rigorous analysis of empirical water use efficiency in different biomes, but the physical processes of biomass accumulation are not accounted for. Although we believe that the ecohydrological responses to climate is likely to hold true at large scales, the regional and seasonal diversities might be more equivocal across ecohydrological models due to the different assumptions and simplifications (such as nitrogen, radiation, mortality, etc.).

The global and regional climate simulations of a 10-year period using CESM, WRF, and WRF/Chem in this work are relatively short compared to a typical length of 30-year period used for most climate model simulations. This is because of constraints in computational resources for performing those model simulations that are computationally very expensive. In particular, WRF/Chem simulations include much more detailed chemistry and aerosol treatments as well as aerosol-cloud interaction processes that have not been considered in most climate models.

This study raises questions about the potential overestimation of precipitation, and thus runoff and GEP in the projections based on existing GCMs and RCMs over the CONUS that do not account for the impact of air pollution (Duan et al. 2016b; Sun et al. 2016). While buffering the warming, atmospheric gases and aerosols are likely to suppress water and carbon fluxes by inducing a significant decline in precipitation. Lack of consideration of the effects of chemistry and aerosol on climate can cause significant prediction errors in future water availability and ecosystem productivity. Further studies on the role of air pollutants in climate change and the interactions of multiple environmental stresses on ecosystem functions are warranted.

Acknowledgments This work was supported by the National Science Foundation EaSM program (AGS-1049200) awarded to North Carolina State University, and the Eastern Forest Environmental Threat Assessment Center (EFETAC), USDA Forest Service. The emissions for chemical species that are not available from the RCP emissions in WRF/Chem simulations are taken from the 2008 NEI-derived emissions for 2006 and 2010 provided by the U.S. EPA, Environment Canada, and Mexican Secretariat of the Environment and Natural Resources (Secretaría de Medio Ambiente y Recursos Naturales-SEMARNAT) and National Institute of Ecology (Instituto Nacional de Ecología-INE) as part of the Air Quality Model Evaluation International Initiative (AQMEII). The authors acknowledge use of the WRF-Chem preprocessor tool mozbc provided by the Atmospheric Chemistry Observations and Modeling Lab (ACOM) of NCAR and the script to generate initial and boundary conditions for WRF based on CESM results provided by Ruby Leung, PNNL. The authors acknowledge high-performance computing support for CESM, WRF, and WRF/Chem simulations from Yellowstone (ark:/85065/d7wd3xhc) provided by NCAR's Computational and Information Systems Laboratory, sponsored by the National Science Foundation and Information Systems Laboratory. Some development work, testing, and initial applications of WRF/Chem were performed on the Stampede Extreme Science and Engineering Discovery Environment (XSEDE) high-performance computing system, which is supported by the National Science Foundation grant number ACI-1053575.

References

Ahlström A, Schurgers G, Arneth A, Smith B (2012) Robustness and uncertainty in terrestrial ecosystem carbon response to CMIP5 climate change projections. Environ Res Lett 7:044008

Burnash R (1995) The NWS river forecast system-catchment modeling. Computer models of watershed hydrology. Water Resources Publications, Littleton, Colorado

Bytnerowicz A, Omasa K, Paoletti E (2007) Integrated effects of air pollution and climate change on forests: a northern hemisphere perspective. Environ Pollut 147:438–445

Caldwell P, Sun G, McNulty S, Cohen E, Moore Myers J (2012) Impacts of impervious cover, water withdrawals, and climate change on river flows in the conterminous US. Hydrol Earth Syst Sci 16:2839–2857

Cheng L, Zhang L, Wang Y-P, Yu Q, Eamus D, O'Grady A (2014) Impacts of elevated CO2, climate change and their interactions on water budgets in four different catchments in Australia. J Hydrol 519:1350–1361

Daly C et al (2008) Physiographically sensitive mapping of climatological temperature and precipitation across the conterminous United States. Int J Climatol 28:2031–2064

Duan K, Mei Y (2014a) Comparison of meteorological, hydrological and agricultural drought responses to climate change and uncertainty assessment. Water Resour Manag 28:5039–5054

Duan K, Mei Y (2014b) A comparison study of three statistical downscaling methods and their model-averaging ensemble for precipitation downscaling in China. Theor Appl Climatol 116:707–719

Duan K, Mei Y, Zhang L (2016a) Copula-based bivariate flood frequency analysis in a changing climate—a case study in the Huai River basin, China. J Earth Sci 27:37–46

Duan K et al. (2016b) Divergence of ecosystem services in U.S. National Forests and Grasslands under a changing climate. Sci Rep. doi:10.1038/srep24441

Forkel R et al (2015) Analysis of the WRF-Chem contributions to AQMEII phase2 with respect to aerosol radiative feedbacks on meteorology and pollutant distributions. Atmos Environ:630–645

Gantt B, He J, Zhang X, Zhang Y, Nenes A (2014) Incorporation of advanced aerosol activation treatments into CESM/CAM5: model evaluation and impacts on aerosol indirect effects. Atmos Chem Phys 14:7485–7497

Ge ZM, Kellomäki S, Zhou X, Wang KY, Peltola H, Väisänen H, Strandman H (2013) Effects of climate change on evapotranspiration and soil water availability in Norway spruce forests in southern Finland: an ecosystem model based approach. Ecohydrology 6:51–63

Gedney N, Cox P, Betts R, Boucher O, Huntingford C, Stott P (2006) Detection of a direct carbon dioxide effect in continental river runoff records. Nature 439:835–838

Gedney N, Huntingford C, Weedon G, Bellouin N, Boucher O, Cox P (2014) Detection of solar dimming and brightening effects on Northern Hemisphere river flow. Nat Geosci 7:796–800

Givati A, Rosenfeld D (2004) Quantifying precipitation suppression due to air pollution. J Appl Meteorol 43:1038–1056

Grell GA, Peckham SE, Schmitz R, McKeen SA, Frost G, Skamarock WC, Eder B (2005) Fully coupled "online" chemistry within the WRF model. Atmos Environ 39:6957–6975

Greve P, Orlowsky B, Mueller B, Sheffield J, Reichstein M, Seneviratne SI (2014) Global assessment of trends in wetting and drying over land. Nat Geosci 7:716–721

He J, Zhang Y (2014) Improvement and further development in CESM/CAM5: gas-phase chemistry and inorganic aerosol treatments. Atmos Chem Phys 14:9171–9200

He J, Zhang Y, Glotfelty T, He R, Bennartz R, Rausch J, Sartelet K (2015a) Decadal simulation and comprehensive evaluation of CESM/CAM5. 1 with advanced chemistry, aerosol microphysics, and aerosol-cloud interactions. J Adv Model Earth Syst 7:110–141

He J et al. (2015b) CESM/CAM5 improvement and application: comparison and evaluation of updated CB05_GE and MOZART-4 gas-phase mechanisms and associated impacts on global air quality and climate. Geosci Model Dev:3999–4025 doi:10.5194/gmd-8-3999-2015

Huang Y, Dickinson RE, Chameides WL (2006) Impact of aerosol indirect effect on surface temperature over East Asia. Proc Natl Acad Sci U S A 103:4371–4376

Hurrell JW et al (2013) The community earth system model: a framework for collaborative research. Bull Am Meteorol Soc 94:1339–1360

Kay A, Rudd A, Davies H, Kendon E, Jones R (2015) Use of very high resolution climate model data for hydrological modelling: baseline performance and future flood changes. Clim Chang 133:193–208

Keenan TF, Hollinger DY, Bohrer G, Dragoni D, Munger JW, Schmid HP, Richardson AD (2013) Increase in forest water-use efficiency as atmospheric carbon dioxide concentrations rise. Nature 499:324–327

Khain A, BenMoshe N, Pokrovsky A (2008) Factors determining the impact of aerosols on surface precipitation from clouds: an attempt at classification. J Atmos Sci 65:1721–1748

Krinner G et al. (2005) A dynamic global vegetation model for studies of the coupled atmosphere-biosphere system. Glob Biogeochem Cycles 19. doi:10.1029/2003GB002199

Noormets A, McNulty SG, DeForest JL, Sun G, Li Q, Chen J (2008) Drought during canopy development has lasting effect on annual carbon balance in a deciduous temperate forest. New Phytol 179:818–828

Pan S, Tian H, Dangal SR, Yang Q, Yang J, Lu C, Tao B, Ren W, Ouyang Z (2015) Responses of global terrestrial evapotranspiration to climate change and increasing atmospheric CO2 in the twenty-first century. Earth's Futur 3(1):15–35

Ramanathan V, Crutzen P, Kiehl J, Rosenfeld D (2001) Aerosols, climate, and the hydrological cycle. Science 294:2119–2124

Ramanathan V et al (2005) Atmospheric brown clouds: impacts on south Asian climate and hydrological cycle. Proc Natl Acad Sci U S A 102:5326–5333

Rosenfeld D et al (2008) Flood or drought: how do aerosols affect precipitation? Science 321:1309–1313

Rudd AC, Kay AL (2015) Use of very high resolution climate model data for hydrological modelling: estimation of potential evaporation. Hydrol Res. doi:10.2166/nh.2015.028

Skamarock WC, Klemp JB, Dudhia J, Gill DO, Barker DM, Wang W, Powers JG (2005) A description of the advanced research WRF version 2. DTIC Document

Sun G, McNulty SG, Moore Myers JA, Cohen EC (2008) Impacts of multiple stresses on water demand and supply across the Southeastern United States. J Am Water Resour Assoc 44:1441–1457

Sun G et al (2011) Upscaling key ecosystem functions across the conterminous United States by a water-centric ecosystem model. J Geophys Res Biogeosci 2005–2012:116

Sun G, Caldwell PV, McNulty SG (2015a) Modelling the potential role of forest thinning in maintaining water supplies under a changing climate across the conterminous United States. Hydrol Process. doi:10.1002/hyp.10469

Sun S, Sun G, Caldwell P, McNulty S, Cohen E, Xiao J, Zhang Y (2015b) Drought impacts on ecosystem functions of the US National Forests and grasslands: part I evaluation of a water and carbon balance model. For Ecol Manag. doi:10.1016/j.foreco.2015.03.054

Sun S, Sun G, Cohen E, McNulty SG, Caldwell PV, Duan K, Zhang Y (2016) Projecting water yield and ecosystem productivity across the United States by linking an ecohydrological model to WRF dynamically downscaled climate data. Hydrol Earth Syst Sci 20:935–952

Tao W-K, Chen J-P, Li Z, Wang C, Zhang C (2012) Impact of aerosols on convective clouds and precipitation. Rev Geophys. doi:10.1029/2011RG000369

Taylor KE, Stouffer RJ, Meehl GA (2012) An overview of CMIP5 and the experiment design. Bull Am Meteorol Soc 93:485–498

Thompson J, Green A, Kingston D (2014) Potential evapotranspiration-related uncertainty in climate change impacts on river flow: an assessment for the Mekong River basin. J Hydrol 510:259–279

Tian H et al (2012) Century-scale responses of ecosystem carbon storage and flux to multiple environmental changes in the southern United States. Ecosystems 15:674–694

USGS, USDA (2013) Federal standards and procedures for the national watershed boundary dataset (WBD) http://www.nrcs.usda.gov/wps/portal/nrcs/main/national/water/watersheds/dataset/.

Wang G, Yu M, Pal JS, Mei R, Bonan GB, Levis S, Thornton PE (2015a) On the development of a coupled regional climate–vegetation model RCM–CLM–CN–DV and its validation in Tropical Africa. Clim Dyn:1–25

Wang K, Zhang Y, Yahya K, Wu S-Y, Grell G (2015b) Implementation and initial application of new chemistry-aerosol options in WRF/Chem for simulating secondary organic aerosols and aerosol indirect effects for regional air quality. Atmos Environ:716–732

Werner A, Cannon A (2015) Hydrologic extremes–an intercomparison of multiple gridded statistical downscaling methods. Hydrol Earth Syst Sci Discuss 12:6179–6239

Wood AW, Maurer EP, Kumar A, Lettenmaier DP (2002) Long-range experimental hydrologic forecasting for the eastern United States. J Geophys Res Atmos 107:4429

Wood AW, Leung LR, Sridhar V, Lettenmaier D (2004) Hydrologic implications of dynamical and statistical approaches to downscaling climate model outputs. Clim Chang 62:189–216

Yahya K, Wang K, Campbell P, Glotfelty T, He J, Zhang Y (2016) Decadal evaluation of regional climate, air quality, and their interactions over the continental US and their interactions using WRF/Chem version 3.6. 1. Geosci Model Dev 9:671–695

Zhang Y (2008) Online-coupled meteorology and chemistry models: history, current status, and outlook. Atmos Chem Phys 8:2895–2932

Zhang Y, Wen X-Y, Jang C (2010) Simulating chemistry–aerosol–cloud–radiation–climate feedbacks over the continental US using the online-coupled weather research forecasting model with chemistry (WRF/Chem). Atmos Environ 44:3568–3582

Zhang Y, Chen Y, Sarwar G, Schere K (2012a) Impact of gas-phase mechanisms on weather research forecasting model with chemistry (WRF/Chem) predictions: mechanism implementation and comparative evaluation. J Geophys Res Atmos 117. doi:10.1029/2011JD015775

Zhang Y et al (2012b) Development and initial application of the global-through-urban weather research and forecasting model with chemistry (GU-WRF/Chem). J Geophys Res Atmos 117. doi:10.1029/2012JD017966

Zhang Y, Chen Y, Fan J, Leung L-YR (2015a) Application of an online-coupled regional climate model, WRF-CAM5, over East Asia for examination of ice nucleation schemes: part II. Sensitivity to heterogeneous ice nucleation parameterizations and dust emissions. Climate 3:753–774

Zhang Y, Zhang X, Wang K, He J, Leung LR, Fan J, Nenes A (2015b) Incorporating an advanced aerosol activation parameterization into WRF-CAM5: model evaluation and parameterization intercomparison. J Geophys Res Atmos 120:6952–6979