IMPACTS OF PROJECTED CLIMATE SCENARIOS ON FUTURE AIR QUALITY AND WATER-CARBON CYCLE IN THE UNITED STATES

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ABSTRACT. – Impacts of projected climate scenarios on future air quality and water-carbon cycle in the United States. Projected changes in anthropogenic emissions and climate changes will impact future air quality, water and carbon cycles, as well as human and environmental health in the United States. In this work, we applied an advanced online-coupled meteorology and chemistry model and an ecohydrological model to simulate such impacts on future air quality, water supplies, and carbon cycles over the continental U.S. for current (2001-2010) and future (2046-2055) years under four climate and emission scenarios including the Representative Concentration Pathways (RCP) 4.5 and 8.5 and the Technology Driver Model (TDM) A1B and B2. A comprehensive evaluation of atmospheric predictions for the current decade using available observations shows an overall good model performance. Future air quality features greater reduction in $PM_{2.5}$ by RCP 4.5/8.5 than TDM B2/A1B and decreased ozone (O_3) over most areas by RCP4.5 and TDM B2, indicating the benefits of carbon policy and technology improvements with greater emission reductions. The climate warming and reduction in precipitation induced by air pollution are projected to lead to a reduction in water yield under both RCP scenarios but an increase in gross ecosystem productivity in some areas under the RCP8.5 scenario. The results show that air pollution is an important factor to be considered in projecting the impacts of climate change on water and carbon cycles at the continental scale.

Keywords: air quality modeling, water-carbon cycle modeling, climate and emission scenarios, WRF/Chem, WaSSI.

1. INTRODUCTION

Projected anthropogenic emission and climate change under various climate scenarios will impact future air quality, water and carbon cycles, as well as human and environmental health. A number of studies have reported projected emissions and/or climate change and the resulting air quality over continental U.S. (CONUS) and its subdomains. For example, Zhang et al. (2008) found that relative

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to levels in 2001 and 2002 summers, maximum 8-h O_3 in 2051 and 2052 summers increases by up to 10.2 ppb (19-20%) over most of the domain due to changes in temperature, solar radiation, and biogenic emissions, while $PM_{2.5}$ decreases by up to 40% under the Forth Assessment Report (AR4) of IPCC A1B scenario. Fiore et al. (2012) reported that annual mean surface O_3 levels increase by 2050 under the Fifth Assessment Report (AR5) of the IPCC Representative Concentration Pathways (RCP) 8.5 scenario but decrease with RCP 2.6, 4.5 and 6.0 over North America. Many studies found that future anthropogenic emissions have a greater influence compared to climate change alone on future air quality (e.g., Hogrefe et al., 2004; Penrod et al., 2014). IPCC AR4 and AR5 projected future anthropogenic emissions based on economic forecasting models by sketching out pathways of economic development under constraints of population and other social factors. However, these projections do not account for changes in future technologies that essentially determine air pollutant emissions. Yan et al. (2014) developed a new Technology Driver Model (TDM) that accounts for changes in future technologies. In this work, TDM is used to project anthrpogenic emissions under two of the four climate and emission scenarios (i.e., IPCC AR4 A1B and B2).

Water resources across the U.S., including traditionally water-rich regions such as the eastern U.S., have been increasingly stressed over the past two decades as a result of population growth and climate change (Gleick, 2003) and many states experience water shortages. Important climatic variables such as near-surface temperature and precipitation can affect soil water storage, evapotranspiration (ET), and runoff (i.e., water yield) in the hydrologic system. Soil moisture and ET in turn affect photosynthesis, carbon uptake, and ecosystem productivity (Duan et al., 2016). Water-carbon cycles can also be affected by air pollution through its feedbacks into regional climate changes (Ramanathan et al., 2005). For example, greenhouse gases (GHGs) can absorb solar radiation and increase temperatures (Bytnerowicz et al., 2007). Atmospheric aerosols may either increase or decrease the formation of precipitation (Rosenfeld et al., 2008; Zhang, 2008). Many ecosystem models have been developed to predict the responses of ecosystem services such as water supply and carbon sequestration to climate change at various scales (McNulty et al., 1996; Sun et al., 2011). Most of these models used coarse-resolution climate projections from general circulation models (GCMs) that cannot well replicate small-scale meteorological phenomena and do not account for the feedbacks between atmospheric pollutants and climate.

In this work, an advanced online-coupled meteorology and chemistry model, the Weather Research and Forecasting Model with Chemistry (WRF/Chem), has been applied to CONUS for current (2001-2010) and future (2046-2055) years under four climate and emission scenarios including the RCP 4.5 and 8.5, and the TDM A1B and B2. Different from offline-coupled models, WRF/Chem can simulate complex feedbacks between air pollutants and climate. It can be applied over CONUS at a higher grid resolution than GCMs. The WRF/Chem-projected climate data under the two RCP scenarios are used to drive the Water Supply Stress Index (WaSSI) model to simulate water and carbon cycles

over CONUS. Our objective is to quantify the impact of projected changes in emissions and climate on future air quality and water and carbon cycles under various scenarios in support of policy making for climate change mitigation.

2. MODEL SETUP AND METHODOLOGY

In this study, we applied the WRF/Chem v3.6.1 with updates in Wang et al. (2015) to simulate air quality and climate under the two RCP scenarios and WRF/Chem v3.7 under the two TDM scenarios. In both versions, the physics options include the Rapid and accurate Radiative Transfer Model for GCM for both shortwave and longwave radiation, the Yonsei University planetary boundary layer scheme and the Morrison double moment microphysics scheme. For cumulus parameterization, the Grell 3D Ensemble is used for RCP simulations whereas the multi-scale Kain Fritsch (MSKF) scheme is used for TDM simulations. Both versions of WRF/Chem use the modified version of 2005 Carbon Bond gas-phase chemical mechanism with chlorine chemistry, the aqueous-phase chemistry module, and the Model for Aerosol Dynamics in Europe with the Volatility Basis Set module for secondary organic aerosol (SOA).

The simulations are performed under the four climate scenarios for current (2001-2010) and future (2046-2055) years using a horizontal resolution of 36×36 km^2. Given different emissions during 2001-2010 between RCP4.5 and 8.5, two sets of 2001-2010 simulations are performed for RCP scenarios. For TDM A1B and B2, only one set of 2001-2010 simulation is performed because their emissions are very similar. The anthropogenic emissions for current period RCP and TDM simulations are based on those of RCP and the U.S. National Emission Inventories, respectively. Biogenic, dust, and seal-salt emissions are calculated online. The chemical and meteorological initial and boundary conditions are generated based on the simulations of Glotfelty et al. (2007) and Glotfelty and Zhang (2007) using the modified Community Earth System Model. For the current decade, a comprehensive climatological evaluation for both climatic and chemical predictions is performed using available observations from surface network and satellites. The evaluation is performed in terms of performance statistics, spatial distributions, and temporal variations based on 10-year averaged results during 2001-2010, following the evaluation protocols of Zhang et al. (2009). The 10-year averaged results during the future and current periods are compared to examine the changes in climate and emissions and their impacts on future air quality. More detailed descriptions on model setup and evaluation methodologies can be found in several studies (Yahya et al., 2017a, b).

For water-carbon cycle simulations, we applied WaSSI for both RCP4.5 and RCP8.5 over CONUS that covers 18 water resources regions (WRR) at the first level, or 82,773 12-digit Hydrologic Unit Code (HUC-12) watersheds at the sixth level (USGS and USDA 2013). WaSSI is an ecohydrological model that estimates water and carbon cycles by biome at HUC-12 watershed scale (Sun et al., 2015). It describes water (i.e., ET, soil moisture, runoff) and carbon (i.e., gross

ecosystem productivity (GEP); respiration (Re); net ecosystem exchange (NEE)) balances by a set of submodels that have been well validated across the U.S. (Sun et al., 2011; Caldwell et al., 2012). The WRF/Chem hourly climate data (i.e., surface air temperature and precipitation) are averaged on a monthly basis, and then bias corrected toward the Parameter-elevation Relationships on Independent Slopes Model (PRISM) dataset using the bias correction and spatial disaggregation method (Werner and Cannon, 2015). The bias corrected precipitation and temperature data are scaled to HUC-12 watersheds and used to drive WaSSI to simulate the ecohydrological processes such as the water and carbon balance for each land cover type within each watershed on a monthly scale.

3. MODEL EVALUATION OF ATMOSPHERIC PREDICTIONS

Table 1 summarizes 10-yr average performance statistics of climatological evaluation. Simulated temperature and relative humidity at 2-m (T2 and RH2) and wind speed and direction at 10-m (WS10 and WD10) are compared against the National Climatic Data Center (NCDC), and show good performance for all three sets of simulations. Simulated precipitation is evaluated against the PRISM datasets. While the TDM simulation with the MSKF cumulus scheme performs well with an NMB of 11.7 %, the two RCP simulations with the Grell 3-D cumulus scheme show larger NMBs of 34.6-37.6 %, indicating uncertainties associated with cumulus schemes. Simulated Max 8-hr average O_3 is compared against the Clean Air Status and Trends Network (CASTNET) and Air Quality System (AQS), and simulated $PM_{2.5}$ is compared against the Interagency for Monitoring Protected Visual Environments (IMPROVE) and the Chemical Speciation Network (CTN). All three simulations perform very well for Max 8-hr average O_3 and 24-hr average $PM_{2.5}$, with NMBs within 11 %, and 15 %, respectively. More detailed performance statistics can be found in Yahya et al. (2017a, b). These results demonstrate the model's capability in capturing long-term climatic and chemical observations.

Table 1. *10-year average performance statistics during 2001-2010*

Variable	Network	RCP4.5		RCP8.5		TDM	
		MB[1]	NMB[2](%)	MB	NMB(%)	MB	NMB(%)
T2 ($^\circ$C)	NCDC	-0.3	-2.3	-0.4	-2.9	-0.6	-4.9
RH2 (%)		2.1	3.0	2.1	3.0	-1.3	-2.0
WS10 (m s^{-1})		0.3	9.4	0.4	10.7	0.2	6.7
WD10 (deg)		23.3	15.0	23.0	14.8	28.4	18.3
Precip (mm day^{-1})	PRISM	0.7	34.6	0.8	37.6	0.3	11.7
Max 8-hr O_3 (ppb)	CASTNET	-4.3	-9.9	-4.8	-11.0	-3.8	-8.5
	AQS	2.2	4.9	1.6	3.5	1.3	2.9
24-hr avg. $PM_{2.5}$ (μg m^{-3})	IMPROVE	0.3	5.6	0.4	6.7	0.8	14.4
	CSN	-1.6	-13.2	-1.7	-13.8	0.8	6.6

[1]MB: mean bias; [2]NMB: normalized mean bias

4. IMPACT OF PROJECTED EMISSIONS AND CLIMATE CHANGE ON FUTURE AIR QUALITY

For carbon monoxide (CO), oxides of nitrogen (NO_x), sulfur dioxide (SO_2), and volatile organic compounds (VOCs), their projected emissions in future decade are lower than current decade, with larger reductions for RCP4.5 compared to RCP8.5. However, ammonia (NH_3) emissions, increase under both scenarios, with larger increases for RCP8.5 compared to RCP4.5. All primary PM emissions such as elemental and organic carbon (EC and OC), unspeciated primary $PM_{2.5}$, and sulfate (SO_4^{2-}) are lower in future decade than current decade, with larger reductions for RCP8.5 compared to RCP4.5 for all species except for SO_4^{2-}. For the RCP4.5 and RCP8.5 simulations, domain-average T2 increases by ~2 °C. Average water vapor mixing ratios at 2-m (Q2) increase in the future climate. Larger changes are simulated for precipitation for RCP8.5 compared to RCP4.5. For RCP4.5, the changes in precipitation show a similar trend to the changes in Q2, (i.e., the largest increases in precipitation occur over the ocean and near the coastal areas), while for the central U.S. there is a decrease in precipitation. For RCP8.5, precipitation generally increases over the whole domain. Similar climate changes are projected under the TBM A1B and B2 scenarios.

The above projected changes in emissions and climate will affect future air quality. Under both RCP scenarios, in responses to changes in their emissions, the mixing ratios of SO_2, NO_x, and CO will decrease and those of NH_3 will increase. For RCP4.5, due mainly to decreases in its precursor emissions, the concentrations of O_3 are reduced by ~ 2 ppb over most parts of the U.S. except for major urban cities in California (CA) and the northeastern U.S. where O_3 is projected to increase up to ~10 ppb. In contrast, the O_3 mixing ratios for RCP8.5 are projected to increase over CONUS with a domain-average increase of ~2.6 ppb and up to ~17 ppb over major cities in the northeastern U.S. and CA. Such O_3 increases are attributed to higher levels of greenhouse gases such as methane (CH_4) and biogenic VOC emissions, decreased NO titration and increased O_3 formation resulted from reduction in NO_x emissions over VOC-limited regions under RCP8.5 compared to RCP4.5. While O_3 is projected to decrease for TDM B2, it will increase under TDM A1B scenario for the same reasons mentioned previously.

$PM_{2.5}$ concentrations for RCP4.5 are projected to decrease over CONUS (except for southern Canada) with a domain-average decrease of ~ 1.5 μg m^{-3} (~ -30 %) due mainly to decreases in the concentrations of its precursors and primary emissions and increased precipitation relative to the current years. $PM_{2.5}$ levels also decrease over the entire U.S. for RCP8.5 with a domain-average decrease of ~1.7 μg m^{-3} (~-35 %) and localized decreases of up to 26 μg m^{-3}. The larger decreases in $PM_{2.5}$ for RCP8.5 as compared to RCP4.5 are due to larger decreases in EC and anthropogenic secondary organic aerosol (SOA) (ASOA). In addition, primary organic aerosol (POA) increases for RCP4.5 but decreases for RCP8.5. Similar to RCP scenarios, the 24-h average $PM_{2.5}$ under both TDM scenarios will decrease over eastern U.S., mainly due to the decreases in the emissions of primary PM and

gaseous precursors and increased precipitation. The decreases are greater under TDM B2 than TDM A1B because of greater projected emission reductions. More detailed results can be found in Yahya et al. (2017a, b).

5. IMPACT OF CLIMAGE CHANGE ON WATER AND CARBON CYCLE

The changing temperature and precipitation will lead to significant decreases in future runoff in most regions. Runoff is expected to decrease significantly by -27 (-10 %) and -11 (-4 %) mm yr^{-1} under RCP4.5 and RCP8.5, respectively. Consistent with the decrease in precipitation in WRR 6, 7, 9-11, and 13, a severe decline in runoff (up to 45 %) is expected to occur in these regions. The exceptional cases are WRR 12, 17, and 18, where an increase is expected under both RCP scenarios. Runoff decrease occurs in more areas when chemistry-climate feedbacks are accounted for, especially in the east. Regional averaged GEP is projected to increase by 3-13 % in all scenarios due to the increases in both temperature and precipitation in the western regions (WRR14-18). Similar consistent increase is also projected in WRR4, 7, 9, and 12. More detailed results can be found in Duan et al. (2016).

6. CONCLUSIONS

The impact of anthropogenic-induced climate change on air quality and water-carbon cycle over CONUS is studied using atmospheric and ecohydrological models. A comprehensive evaluation of the atmospheric model, WRF/Chem, for current decade is conducted for current decade using available long-term observations from surface networks and satellites. Our results show an overall good performance for both climatic and chemical variables, illustrating its ability to project future climate changes and impacts on air quality, water supplies, and carbon cycles. Future air quality features greater reduction in $PM_{2.5}$ by RCP 4.5/8.5 than TDM B2/A1B and decreased O_3 over most areas by RCP4.5 and TDM B2. However, projected O_3 increases under RCP8.5 and TDM A1B, due to high GHGs level and BVOC emissions, reduced NO titration, and enhanced O_3 formation resulted from NO_x reduction over VOC-limited regions. These results indicate the benefits of carbon policy and technology changes with greater emission reductions. In particular, O_3 and $PM_{2.5}$ may be better controlled by reducing emissions of their precursors and GHGs with greater benefits under TDM/B2 than TDM/A1B.

Our ecohydrological simulation results using WaSSI show that air pollution tends to suppress water and carbon fluxes from the atmosphere and leads to decline in both runoff and GEP, aggravating the impacts of regional climate change on water supply. When the chemistry-climate feedbacks are considered, projected climate change will lead to a reduction in water yield under both RCP scenarios but an increase in ecosystem ET and GEP and a decrease in NEE for RCP8.5. These results indicate the importance of win-win emission control

strategies that can mitigate problems related to adverse climate change, air pollution, and water shortages.

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REFERENCES

1. Bytnerowicz A., Omasa K., and Paoletti E. (2007), *Integrated effects of air pollution and climate change on forests: a northern hemisphere perspective*. Environ Pollut 147, 438–445.
2. Caldwell P., Sun G., McNulty S., Cohen E., and 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.
3. Duan, K., G. Sun, Y. Zhang, K. Yahya, K. Wang, J. M. Madden, P. V. Caldwell, E. C. Cohen, and S. G. McNulty (2016), *Impact of air pollution induced climate change on water availability and ecosystem productivity in the conterminous United States*, Climate Change, DOI 10.1007/s10584-016-1850-7.
4. Fiore, A. M., V. Naik, D. V. Spracklen, A. Steiner, N. Unger, M. Prather, D. Bergmann, P. J. Cameron-Smith, I. Cionni, W. J. Colins, S. Dalsøren, V. Eyring, G. A. Folberth, P. Ginoux, L. W. Horowitz, B. Josse, J.-F. Lamarque, I. A. MacKenzie, T. Nagashima, F. M. O'Connor, M. Righi, S. T. Rumbold, D. T. Shindell, R. B. Skeie, K. Sudo, S. Szopa, T. Takemura, G. Zeng (2012), *Global air quality and climate*, Chem. Soc. Rev. 41, 6663-6683.
5. Gleick, P.H. (2003), *Water: The Potential Consequences of Climate Variability and Change. Report of the National Water Assessment Group for the U.S. Global Change Research Program*. Pacific Institute, USGS, Oakland, California. 151 pp.
6. Glotfelty, T., J. He, and Y. Zhang (2017), *The Impact of Future Climate Policy Scenarios on Air Quality and Aerosol/Cloud Interactions using an Advanced Version of CESM/CAM5: Part I. Model Evaluation for the Current Decadal Simulations*, Atmos. Environ. 152, 222–239, doi: 10.1016/j.atmosenv.2016.12.035.
7. Glotfelty, T. and Y. Zhang (2017), *The Impact of Future Climate Policy Scenarios on Air Quality and Aerosol/Cloud Interactions using an Advanced Version of CESM/CAM5: Part II. Future Trend Analysis and Impacts of Projected Anthropogenic Emissions*, Atmos. Environ. 152, 531-552.
8. Hogrefe, C., Lynn, B., Civerolo, K., Ku, J., Rosenthal, J., Rosenzweig, C., Goldberg, R., Gaffin, Knowlton, S., K., Kinney, P. (2004), *Simulating changes in regional air*

pollution over the eastern United States due to changes in global and regional climate and emissions. JGR, 109(D22), D22301, doi:10.1029/2004JD004690, 2004.

9. McNulty, S.G., J.M. Vose, W.T. Swank (1996), *Loblolly pine hydrology and productivity across the southern United States*. Forest Ecology and Management 86, 241-251.

10. Penrod, A., Y. Zhang, K. Wang, S.-Y. Wu, and R. L. Leung (2014), *Impacts of Future Climate and Emission Changes on U.S. Air Quality*, Atmos. Environ. 89, 533-547, doi:10.1016/j.atmosenv.2014.01.001.

11. 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.

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

13. Sun S., Sun G., Caldwell P., McNulty S., Cohen E., Xiao J., Zhang Y. (2015), *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

14. 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/.

15. Sun G. et al. (2011), *Upscaling key ecosystem functions across the conterminous United States by a water-centric ecosystem model*. JGR Biogeosci 116, 2005–2012.

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

17. Wang, K., Y. Zhang, K. Yahya, S.-Y. Wu, and G. Grell (2015), *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., 115, 716-732, doi:10.1016/j.atmosenv.2014.12.007.

18. Yahya, K., K. Wang, P. Campbell, Y. Chen, T. Glotfelty, J. He, M. Pirhalla, and Y. Zhang (2017a), *Decadal Application of WRF/Chem for Regional Air Quality and Climate Modeling over the U.S. under the Representative Concentration Pathways Scenarios. Part 1: Model Evaluation and Impact of Downscaling*, Atmos. Environ., 152: 562–583, doi: 10.1016/j.atmosenv.2016.12.029.

19. Yahya, K., P. Campbell, and Y. Zhang (2017b), *Decadal Application for Regional Air Quality and Climate Modeling over the U.S. under the Representative Concentration Pathways Scenarios. Part 2: Current vs. Future WRF and WRF/Chem simulations*, Atmos. Environ*., 152, 584–604, doi: 10.1016/j.atmosenv.2016.12.028.

20. Yan, F., E. Winijkul, D. G. Streets, Z. Lu, T. C. Bond, and Y. Zhang (2014), *Global Emission Projections for the Transportation Sector using Dynamic Technology Modeling*. Atmos. Chem. and Phys. 14, 5709–5733, doi:10.5194/acp-14-5709-2014.

21. Zhang, Y. (2008), *Online Coupled Meteorology and Chemistry models: History, Current Status, and Outlook*, Atmos. Chem. and Phys. 8, 2895-2932.

22. Zhang, Y., Hu, X., Leung, L. R., W. I. Gustafson Jr. (2008), *Impacts of regional climate change on biogenic emissions and air quality*. JGR, 113(D18), D18310.

23. Zhang, Y., K. Vijayaraghavan, X.-Y. Wen, H. E. Snell, and M.Z. Jacobson (2009), *Probing Into Regional Ozone and Particulate Matter Pollution in the United States: 1. A 1-year CMAQ Simulation and Evaluation Using Surface and Satellite Data*, JGR, 114, D22304, doi:10.1029/2009JD011898.