Environmental Research Letters

LETTER

Simulating the impacts of chronic ozone exposure on plant conductance and photosynthesis, and on the regional hydroclimate using WRF/Chem

Jialun Li\textsuperscript{1,4}, Alex Mahalov\textsuperscript{1,2} and Peter Hyde\textsuperscript{3}

\textsuperscript{1} School of Mathematical and Statistical Sciences, Arizona State University, Tempe, AZ 85287, USA
\textsuperscript{2} Julie Ann Wrigley Global Institute of Sustainability, Arizona State University, Tempe, AZ 85287, USA
\textsuperscript{3} School for Engineering of Matter, Transport and Energy, Arizona State University, Tempe, AZ 85287, USA
\textsuperscript{4} Author to whom any correspondence should be addressed.

E-mail: Jialun.Li@asu.edu

Keywords: WRF/Chem, chronic ozone, hydroclimate effect, plant conductance and photosynthesis

Supplementary material for this article is available online

Abstract

The Noah-Multiparameterization land surface model in the Weather Research and Forecasting (WRF) with Chemistry (WRF/Chem) is modified to include the effects of chronic ozone exposure (COE) on plant conductance and photosynthesis (PCP) found from field experiments. Based on the modified WRF/Chem, the effects of COE on regional hydroclimate have been investigated over the continental United States. Our results indicate that the model with/without modification in its current configuration can reproduce the rainfall and temperature patterns of the observations and reanalysis data, although it underestimates rainfall in the central Great Plains and overestimates it in the eastern coast states. The experimental tests on the effects of COE include setting different thresholds of ambient ozone concentrations ([O\textsubscript{3}]) and using different linear regressions to quantify PCP against the COE. Compared with the WRF/Chem control run (i.e., without considering the effects of COE), the modified model at different experiment setups improves the simulated estimates of rainfall and temperatures in Texas and regions to the immediate north. The simulations in June, July and August of 2007–2012 show that surface [O\textsubscript{3}] decrease latent heat fluxes (LH) by 10–27 W m\textsuperscript{-2}, increase surface air temperatures (T\textsubscript{2}) by 0.6 °C–2.0 °C, decrease rainfall by 0.9–1.4 mm d\textsuperscript{-1}, and decrease runoff by 0.1–0.17 mm d\textsuperscript{-1} in Texas and surrounding areas, all of which highly depends on the precise experiment setup, especially the [O\textsubscript{3}] threshold. The mechanism producing these results is that COE decreases the LH and increases sensible heat fluxes, which in turn increases the Bowen ratios and air temperatures. This lowering of the LH also results in the decrease of convective potential and finally decreases convective rainfall. Employing this modified WRF/Chem model in any high [O\textsubscript{3}] region can improve the understanding of the interactions of vegetation, meteorology, chemistry/emissions, and crop productivity.

1. Introduction

Vegetation has a strong effect on climate through regulating energy, water, and carbon cycles at multiple scales (McPherson 2007). The ability of a plant to regulate leaf water loss in most situations is simply controlled by stomatal behavior (Cowan and Thoughto 1971); however, the rate of plant carbon assimilation or photosynthesis is jointly controlled by both stomatal function and mesophyll biochemical and transport processes. Usually, photosynthesis and stomatal conductance are tightly coupled. Models, such as the Ball-Berry model of stomatal conductance commonly used in describing dynamical vegetation, calculate stomatal conductance based on photosynthetic values. They accurately reproduce observational photosynthesis and stomatal conductance under ideal conditions (e.g., see Lombardozzi et al 2012, 2015 and
the references therein), but they fail to accurately simulate stomatal conductance, transpiration, and carbon assimilation under the oxidative stress caused by ozone (O\textsubscript{3}) exposure (e.g., see review references of Ainsworth et al 2012, von Schneidemesser et al 2015, and the references therein), because O\textsubscript{3} damages plant tissues and disrupts their metabolism. Furthermore, O\textsubscript{3} damage to any of the carbon assimilation processes ( stomatal function, mesophyll biochemical processes or transport processes) at unequal rates or magnitudes will cause photosynthesis and stomatal conductance (which affects transpiration) to become decoupled (e.g., Tjoelker et al 1995, Saldatini et al 1998, Novak et al 2005, Paolleti and Grulke 2005, Calatayud et al 2007, Francini et al 2007, Lombardozzi et al 2012, 2015 and the references therein), indicating that any mathematical models describing plants’ photosynthesis and stomatal conductance need to account for the effect of ozone exposures when ozone concentrations ([O\textsubscript{3}]) reach certain levels, one of our motivations in this study.

Ozone is a secondary pollutant formed from the action of sunlight on nitrogen oxides (NOx), produced mainly from vehicular and other large engine combustion and biomass burning, in the presence of volatile organic compounds (VOCs) of both natural and anthropogenic origin. In addition to being known as a greenhouse gas (IPCC 2007) and a harmful pollutant to human beings (e.g., see review of von Schneidemesser et al 2015), O\textsubscript{3} can penetrate the leaves of plants through the stomata to oxidize plant tissue, impair photosynthesis, affect the metabolic activity, and reduce stomatal conductance (Reich 1987). Field experiments demonstrate that ozone exposures reduce crop yields (e.g., Ainsworth et al 2012 and reference therein), decrease evapotranspiration (ET), increase canopy temperature and soil moisture (e.g., Bernacchi et al 2011, VanLooocke et al 2012); and therefore exert potentially large influences on the global carbon and water cycling and on other aspects of the hydroclimatic (McLaughlin et al 2007, Sitch et al 2007, Felzer et al 2009, Lombardozzi et al 2015). The deleterious effects on crops and forests due to O\textsubscript{3} exposure have already had negative economic consequences (Van Dingenen et al 2009, Wittig et al 2009, Avnery et al 2011, McGrath et al 2015). The adverse effects on vegetation and ecosystems are expected to remain a risk in the coming decades (e.g., Felzer et al 2007, Ainsworth et al 2012, von Schneidemesser et al 2015).

In addition to field experiments, an alternative way to investigate ozone damage to plants and their prevailing hydroclimate is to use mathematical models, especially process-based numerical models that can incorporate the experimental results and explore large regions (Felzer et al 2007). These model investigations include addressing the effects of surface [O\textsubscript{3}] on photosynthesis (e.g., Sitch et al 2007, Kvalevag and Myhre 2013), crop yields (e.g., Tai et al 2014, Avnery et al 2011, McGrath et al 2015), and water cycles (e.g., Felzer et al 2009, Lombardozzi et al 2015). For example, Felzer et al (2009) have investigated the effect of carbon dioxide, nitrogen in the soil, and O\textsubscript{3} on hydrology. They found that a combination of nitrogen limitation and O\textsubscript{3} damage on photosynthesis increases runoff by 6%–11%. Failure to consider the effects of the interactions among nitrogen, O\textsubscript{3}, and elevated CO\textsubscript{2} may lead to significant regional underestimates of future runoff. In their study, however, the ecosystem model (dynamical vegetation model) was not coupled with an atmospheric model (i.e., meteorological forcings such as precipitation and temperature were prescribed) and, in a further weakness, their study did not consider the unequal damage rates (or decoupling) induced by O\textsubscript{3} between stomatal conductance and photosynthesis discussed by Lombardozzi et al (2012, 2015). Collins et al (2010), using a one-way coupled chemistry model, terrestrial carbon model, and a simple analytic climate model, have studied how O\textsubscript{3} precursors affect vegetation and climate. Their results indicate that temperature changes vary depending on location and vegetation type. However, they have not investigated how O\textsubscript{3} precursors affect hydrologic cycles since simple analytic climate model was used. In these kinds of studies, however, the ecosystem model, meteorological model and chemical model are not coupled with each other.

Super et al (2015) have examined the seasonal O\textsubscript{3} impact on stomatal resistance, surface energy balance, planetary boundary layer (PBL) dynamics, and CO\textsubscript{2} assimilation at a diurnal scale. They have two-way coupled a seasonal canopy resistance module with a PBL model that solves the diurnal evolution of dynamical and chemical variables in a well-mixed, convective boundary layer. Their study indicates that CO\textsubscript{2} assimilation decreases as much as 15% due to O\textsubscript{3} damage. Super et al (2015) have not investigated atmospheric processes above the PBL and hydroclimate variables such as precipitation and runoff due to ozone exposure. In the study of Super et al moreover, they have not accounted for ozone’s unequal damage rates to stomatal conductance and photosynthesis as discussed by Lombardozzi et al (2012, 2015) and others.

Lombardozzi et al (2012), based on the unifying theory proposed by Reich (1987) and Nunn et al (2006), have developed a method that quantitatively describes the phenomenon of unequal damage rates through parameterizing the effects of chronic O\textsubscript{3} exposure (COE) on stomatal conductance photosynthesis, separately. The results of Lombardozzi et al (2012) suggest that independently modifying stomatal conductance can improve the ability of models to predict hydrologic cycling, and therefore improve future climate predictions. Lombardozzi et al (2015), using the Community Land Model (CLM) and hourly [O\textsubscript{3}] generated from the Community Atmospheric Model, have investigated gross primary production (GPP), ET, and runoff changes over global land affected by COE. They found that COE decreases GPP by 8%–
12%, decreases ET by 2%–4%, and increases runoff by as much as 15% in the eastern US. Lombardozzi et al (2015) used the Ball-Beery stomatal conductance model, in which ozone’s unequal damage rates to stomatal conductance and photosynthesis are considered and the effects of COE on different types of vegetation are also accounted for. However, since the offline CLM is used (i.e., CLM are not two way coupled with the meteorological and chemical models), Lombardozzi et al (2015) have not investigated the non-radiative effects of COE on surface temperature and precipitation, both of which affect vegetation’s transpiration and photosynthesis as well as photochemical reaction rates and ultimately [O₃] themselves, the main scientific focus of our study.

Note that Sun et al (2012), based on statistical models and observations, have found that O₃ at near ambient concentrations can reduce stomatal control of leaf transpiration, increase water use, increase ET, and reduce streamflow. The results from Sun et al (2012) contradict with some model results (e.g., Felzer et al 2009, Lombardozzi et al 2015) and appear to be inconsistent with field experiments (e.g., Bernacchi et al 2011, VanLooye et al 2012). The reasons for these disagreements could be: (1) McCaughlin et al (2007) and Paoletti and Grukle (2010) reported that with chronic exposure, O₃ can also cause stomata to respond sluggishly to environmental cues, increasing stomatal conductance and rates of transpiration, therefore decreasing soil moisture and streamflow (as reported by Sun et al 2012); (2) locations differ between the experimental studies (by Bernacchi et al 2011 and VanLooye et al 2012) and the statistical studies (by Sun et al 2012); (3) experiments from Bernacchi et al 2011 and VanLooye et al 2012 are conducted at the canopy scale while statistical studies from Sun et al 2012 are conducted at the much larger watershed/regional scale; and (4) due to offline ecosystem models used in Felzer et al (2009) and Lombardozzi et al (2015), the ozone-induced ET reductions in vegetated regions cannot alter atmospheric processes, which themselves affect surface layer characteristics such as hydroclimate fields such as ET, precipitation, and runoff, a fact that has already been documented (e.g., Mahalov et al 2016, Pei et al 2016), and calls for study using two-way coupled model systems.

In this study, the Weather Research and Forecasting (Skamarock et al 2008) with chemistry model (WRF-Chem) (Grell et al 2005) is modified by adding the non-radiative forcing effects of ozone exposure on the photosynthesis and stomatal conductance of vegetation. Our objective is to better understand the effects of COE on vegetation’s ET and subsequently on hydroclimate (such as surface temperatures, precipitation, and runoff) as well as the feedbacks to ozone chemistry at regional scale, a study not yet conducted (Sun et al 2012, von Schneidemesser et al 2015). The description of model modifications and setup is given in section 2. The model experimental setup, verification and application are in section 3, and conclusions are summarized in section 4.

2. Method

2.1. WRF-Chem modification and setup

The WRF-Chem modules include atmospheric physics and dynamical processes, atmospheric chemistry, and biophysical and biochemical processes (Grell et al 2005, Skamarock et al 2008). The system, coupled in a two-way mode, has been widely used to simulate air-quality and atmospheric physics–chemistry interactions (e.g., Zhang et al 2007, Yegorova et al 2011, Tao et al 2013, Li et al 2014, 2016, Kong et al 2015). However, the module on the effects of COE on photosynthesis and stomatal conductance has not been included in the standard WRF-Chem, although ozone’s radiative forcing effects are parameterized in it.

2.1.1. Implementation of ozone damage to plant’s photosynthesis and conductance into Noah-Multiparameterization land surface model (Noah-MP) in WRF-Chem

In this study, we add the processes of COE to the standard WRF-Chem (v3.7.1) model using the parameterization scheme developed by Lombardozzi et al (2012, 2015). The plant photosynthesis and leaf stomatal conductance are adjusted, separately, based on the unifying theory of Reich (1987) that was validated in different vegetation types (e.g., Olinger et al 1997, Nunn et al 2006, Wittig et al 2007). We selected this scheme since Lombardozzi et al (2015) have suggested relevant parameters based on previous field experiments and model studies, and have implemented this method into the CLM to estimate GPP, transpiration, and grid runoff at a global scale. Note that the Ball-Berry model is used both in CLM and in Noah-MP in the standard WRF-Chem model. Therefore, we add the effects of COE on plant’s photosynthesis and leaf stomatal conductance into CLM and Noah-MP of the standard WRF-Chem. Details of the method and mathematical equations can be found in the supplemental materials.

2.1.2. Implementation of agricultural irrigation into Noah-MP in WRF-Chem

As with the lack of COE effects on photosynthesis and stomatal conductance discussed above, agricultural irrigation is not implemented into the standard WRF-Chem model (Li et al 2016). Previous studies indicate that vegetation is more sensitive to soil water stress than to COE (Nunn et al 2006, Hayes et al 2012, Super et al 2015). To address the effect of COE, we first need to realistically simulate the actual soil water stress. Therefore, we add an irrigation scheme for the irrigated lands (about 61.1 million acres or 5.5% of total agricultural land in the US in 2005 http://water.
usgs.gov/edu/wuir.html), which consume 128 000 million gallons of water per day. The irrigation scheme is based on Sorooshian et al (2011, 2012 and 2014) and was implemented into Noah in WRF/Chem (Li et al 2016) for irrigated agricultural and arid/semi-arid urban vegetated lands. In this study, we transfer the same irrigation scheme into Noah-MP in the standard WRF/Chem (v3.7.1). We choose the year 2010 to examine the effects of irrigation on precipitation in the US. Our irrigation sensitivity tests for this year indicate that with the irrigation scheme the magnitude and spatial distribution of precipitation better matched the observations than that without irrigation. The results are not discussed here since many studies have investigated this topic (e.g., DeAngelis et al 2010, Harding and Snyder 2012, Huber et al 2014, Alter et al 2015, Harding et al 2015, Mahalov et al 2016, Pei et al 2016).

2.1.3. WRF/Chem setup

WRF/Chem includes multiple physics and chemistry parameterization schemes; many studies have investigated the effects of these different physical/chemical schemes on model results (e.g., Misenis and Zhang 2010, Hu et al 2013, Cuchiarra et al 2014; and many others). Here, we selected the modified YSU surface layer and PBL schemes (Hong et al 2006); the Morrison double-moment microphysics scheme (Morrison et al 2009); the RRTMG radiation scheme (Iacono et al 2008); the Noah-MP land surface scheme (Niu et al 2011); and the Grell–Devenyi ensemble cumulus scheme (Grell and Devenyi 2002). Land cover and land use data from the United States Geological Survey 1 km resolution dataset (including irrigation lands) are combined with the 2006 National Land Cover Database 3-class urban covers to better represent the urban landscape. For the atmospheric chemistry mechanism, we chose the Model for OZone and Related Chemical Tracers (MOZART) chemical mechanism (Emmons et al 2010), which combines the MOZART gas chemistry treatment with the Goddard Chemistry Aerosol Radiation and Transport approach or GOCART (Ginoux et al 2001). The photolysis scheme is based on the Madronich Fast-TUV photolysis module (Tie et al 2003). The other physics and chemistry parameterization schemes are the same as Li et al (2016).

To reduce computational expense, a single domain is used, which covers the contiguous United States and surrounding lands (including, southern Canada, northern Mexico, and Cuba), and oceans (eastern Pacific, western Atlantic, and the Gulf of Mexico). The vertical configuration of the model comprises 41 full layers: the lowest 15 layers are within 1500 m above ground level (agl), and the first half-vertical layer above ground surface is about 21.5 m agl.

2.2. Data used for model forcing and evaluation

The 6 hourly and 0.5° final analysis reanalysis data are used as meteorological forcing. Anthropogenic emissions data are from EDGAR, which have 0.1° global coverage based on emissions of 2010 (edgar.jrc.europa.eu). The daily fire data can be downloaded from web (http://bai.acom.ucar.edu/Data/fire/). Chemistry lateral boundary data are downloaded from MOZART (http://acom.ucar.edu/wrf-chem/mozart.shtml). The data for model performance are downloaded from (http://rda.ucar.edu/datasets/ds608.0/), which are 3 hourly and 32 km resolution North American Regional Reanalysis (NARR) data (Mesinger et al 2006). The gridded gauge precipitation data, generated by the US Climate Prediction Center (CPC), are assimilated into the NARR system. Therefore, NARR precipitation can be treated with gridded gauge data.

3. Results and discussion

Based on the availability of chemistry lateral boundary data and emissions data, the test years selected are 2007–2012, and for each year the model is run from April 1 to September 30. Data from the first 30 d’ simulations are discarded. Two types of runs are conducted: the control run (CTRL), running standard WRF/Chem with an irrigation scheme, and the test runs or fully two-way coupled (FCPL) runs, running WRF/Chem the same as CTRL but with the effects of COE on vegetation photosynthesis and leaf stomatal conductance being added. Specifically, we conducted three experiments with the FCPL runs. Experiment 1 is called FCPL-SLOP-O40 or SLOP-O40: it assumes ozone damage to plants occurs when the [O₃] threshold is lowered to 40 ppb (O40) and the linear regression (showing as equations S2 and S3 in supplement) includes both slope (SLOP) and intercept. Experiment 2 is called FCPL-NOSLOP-O40 or NOSLOP-O40: it is the same as Experiment 1 but without the slope term in the linear regression (i.e., only the intercept term that is shown in equations S2 and S3), and Experiment 3 is called FCPL-SLOP-O20 or SLOP-O20: the same as Experiment 1 but the [O₃] threshold is lowered to 20 ppb (O20).

3.1. Model evaluation to the mean fields

A realistic model ‘climatology’ is a crucial prerequisite for examining the hydroclimate response to changes in the vegetation’s photosynthesis and conductance due to COE; hence, the importance of evaluating model performance. The mean 2 m air temperature distributions during the simulations are show in figure S1 (see supplementary materials). The model reproduces the spatial distribution very well as indicated by the NARR data. Averaged throughout the continental United States, the multiple-year gridded means are 21.76 °C for NARR, 21.45 °C for CTRL, 21.62 °C for
SLOP-O40, 21.66 °C for NOSLOP-O40, and 22.43 °C for SLOP-O20. The correlation coefficient and mean biases are 0.96 °C and −0.31 °C between CTRL and NARR, 0.96 °C and −0.14 °C between SLOP-O40 and NARR, 0.96 °C, and −0.1 °C between NOSLOP-O40 and NARR, and 0.95 °C and 0.67 °C between SLOP-O20 and NARR. Compared to NARR, the runs of SLOP-O40 and NOSLOP-O40 improve the CTRL by 0.2 °C while the run of SLOP-O20 shows warm biases by 0.7 °C at the domain average. The year-by-year statistical results, shown in table S1, have similar trends. Figure 1 presents the mean bias (% relative to NARR) comparison of 2 m air temperatures between simulations and reanalysis data (i.e., NARR) during the simulation time periods. The model generates warm biases in the central Great Plains and northwestern interior states (Colorado, Utah, and Idaho) at about 10%−20% (with a magnitude of 0.5 °C−2.5 °C), while it generates cool biases in Texas and surrounding regions at about −10% to −20% (with a magnitude of −0.5 °C to −3 °C). For the SLOP-O20 run, the model generates warm biases in the Central US at about 10%−20% while it significantly reduces the cool biases in the southwestern US and northern Mexico. Table S2 is the same as table S1 but only for the focused areas within the box in figure 1. Table S2 indicates that although the O20 run generates warm biases, the changes are much consistent compared with other runs.

Figure S2 presents the comparison of precipitation between simulations and reanalysis data during the simulation time periods (May through September). Although the model generally reproduces the precipitation patterns exhibited by the NARR data, it underestimates precipitation in the central Great Plains, a clear model deficiency but at least consistent with previous studies for example, Jiang et al (2009), using WRF with Noah-MP in dynamical vegetation mode, have found that WRF underestimates the precipitation over 1.0 mm d$^{-1}$ in the Great Plains. Harding et al (2015), using WRF with CLM in the dynamical vegetation mode, have simulated the warm season precipitation in the Great Plains and their results indicate that the model underestimates precipitation by as much as 100% with a domain average of 25%. Figure S2 also shows that WRF/Chem
overestimates the precipitation over the eastern states, attributed to the runoff scheme and lateral boundary effects (Jiang et al. 2009). Table S2 shows the statistical results for the continental US. The multiple-year gridded mean are 2.24 mm d\(^{-1}\) for NARR, 2.90 mm d\(^{-1}\) for CTRL, 2.85 mm d\(^{-1}\) for SLOP-O40, 2.85 mm d\(^{-1}\) for NOSLOP-O40 and 2.55 mm d\(^{-1}\) for SLOP-O20. The correlation coefficient and biases are 0.71 and 0.66 mm d\(^{-1}\) between CTRL and NARR, 0.71 and 0.61 mm d\(^{-1}\) between SLOP-O40 and NARR, 0.71 and 0.59 mm d\(^{-1}\) between NOSLOP-O40 and NARR, and 0.69 and 0.31 mm d\(^{-1}\) between SLOP-O20. Table S3 also shows the year-by-year statistical results for the domain average. Results from table S3 indicate that FCPL runs, especially O20 run, reduce biases, compared with the CTRL run. Figure 2 shows the spatial distributions of precipitation biases (% relative to NARR), which indicates that the model improves precipitation significantly, compared with the CTRL runs; including in Texas, New Mexico, Oklahoma, and Nebraska, the precipitation overestimation from CTRL is mitigated. Table S4 is the same as table S3 but for the statistical results over the region in the box shown in figure 2. With the SLOP-O20 run, correlation coefficients increase and bias magnitudes decrease and they do so consistently.

Note that the modeled precipitation is greater than the NARR data in the mountainous regions of the western US and Mexico. On the one hand, the spatial distribution of precipitation is somewhat compromised due to the lack of densely distributed rain gauges restricted by complex topography (Nesbitt et al. 2004, Chen et al. 2008). On the other hand, the model has the feature that convection can be easily triggered over mountains.

Figure S3 (presented in supplement) shows the daily maximum 8 h average (DMA8) \([\text{O}_3]\) with data being averaged from CTRL and three FCPL runs. The data are averaged in June, July, and August from 2007 to 2012. High DMA8 \([\text{O}_3]\) mainly are found in the western mountainous regions, and east and south coasts with multiyear averages up to 40 ppb. The lower DMA8 \([\text{O}_3]\) are in the Great Lakes and surrounding regions with multiyear averages of less than 30 ppb. Li et al. (2016), using WRF/Chem at 4 km resolution in California and 12 km resolution in the United States, have simulated DMA8 \([\text{O}_3]\) in one warm season (July and August) and noted that WRF/Chem under-estimated \([\text{O}_3]\), especially for elevated ozone events, due to biased meteorological fields in the long-term runs, in comparison with ozone observations. Furthermore, to realistically simulate surface \([\text{O}_3]\), 4 km resolution of WRF/Chem may be too coarse in the
southwestern United States, compared with site-observations (Li et al. 2015, 2016). In other words, the DMA8 \(\text{[O}_3\text{]}\) shown in figure S3 underestimated the observations, so the ozone damage to plants are likely underestimated for the O40 runs, as well.

In general, our model simulations can reproduce the precipitation and temperature spatial patterns well and are comparable with previous studies. With the effects of COE on plants being implemented, FCPL runs significantly improve the CTRL run in temperature and precipitation over the regions from Texas and New Mexico northward to Wyoming and South Dakota. Therefore, this model configuration can be used for further simulation studies.

3.2. Changes of hydroclimate fields in response to ozone chronic exposure

The changes of process-based hydroclimate fields in a model system can be analyzed if there are the same patterns between control run and sensitivity run, even if the model underestimates/overestimates (Harding and Snyder 2012, Harding et al. 2015). In comparing WRF/Chem CTRL with WRF/Chem FCPL runs shown in figures S1–S3, the results exhibit similar patterns, including the locations of overestimations and underestimations, and therefore contained no systematic biases. Analogous to the processing of Harding and Snyder (2012) and Harding et al (2015),

the changes of hydroclimate fields induced by COE are discussed in this subsection.

Figures 3(a)–(c) present DMA8 \(\text{[O}_3\text{]}\) differences between FCPL runs and CTRL runs (FCPL minus CTRL): (a) between FCPL-SLOP-O40 and CTRL, (b) between FCPL-NOSLOP-O40 and CTRL, and (c) between FCPL-SLOP-O20 and CTRL. (d)–(f) Scatter plot between accumulative ozone (see supplement for explanation) from different FCPL runs and accumulated transpiration differences between FCPL run and CTRL run. (a), SLOP-O40, (b), NOSLOP-O40, (f), SLOP-O20. Data are averaged in the box shown in figure 2 for June, July and August in 2007–2012.

![Figure 3](image-url)

Figure 3. (a)–(c) Differences of daily 8 h maximum average (DMA8) ozone concentrations (\(\text{[O}_3\text{]}\)) between WRF/Chem CTRL run and FCPL runs (FCPL minus CTRL): (a) between FCPL-SLOP-O40 and CTRL, (b) between FCPL-NOSLOP-O40 and CTRL; and (c) between FCPL-SLOP-O20 and CTRL. (d)–(f) Scatter plot between accumulative ozone (see supplement for explanation) from different FCPL runs and accumulated transpiration differences between FCPL run and CTRL run. (a), SLOP-O40, (b), NOSLOP-O40, (f), SLOP-O20. Data are averaged in the box shown in figure 2 for June, July and August in 2007–2012.
model cumulative ozone and CTDs cannot be seen in figures 3(d) and (e). Therefore, we mainly focus on the SLOP-O20 run in the following discussion.

Figure 4 displays the meteorological changes over land between FCPL-SLOP-O20 and CTRL. The data over land that cannot pass the 95% significance-level of the Student-t test are masked as gray (data over water are not analyzed and the discussion is focused on the area of the box indicated in figure 4). Ozone damage causes the latent heat flux heat (LH) to decrease as shown in figure 4(c) (decreasing transpiration shown in figures 3(d)–(f)) while net radiation (Rnet) decreases (figure 4(a)). This variation of LH and Rnet increases the Bowen ratios (not shown) and sensible heat fluxes (HFX, shown in figure 4(b)), and therefore increases air temperatures (figure 4(d)) and PBL height (figure not shown, but see table 1 for their magnitudes). The ozone damage also decreases the moist static energy (MSE, see figure 4(e)) and column precipitable water (see figure 4(f)), which results in the decrease of convective potential (Harding and Snyder 2012, Mahalov et al 2016) and finally decreases
Table 1. Changes of meteorological variables in the focused area (shown as the box in figure 4) between CTEL run and CFPL runs. The data are averaged over those grid cells whose data meet the 95% significance in the Student’s t-test.

|                | SLOP-O40 | NOSLOP-O40 | SLOP-O20 | SLOP-O40 | NOSLOP-O40 | SLOP-O20 |
|----------------|----------|------------|----------|----------|------------|----------|
| Rnet (W m⁻²)   | -4.8     | -3.5       | -12.0    | -0.33    | -0.35      | -0.93    |
| HFX (W m⁻²)    | 8.3      | 8.3        | 17.7     | 0.68     | 0.79       | 2.11     |
| LH (W m⁻²)     | -9.9     | -10.3      | -27.1    | -0.91    | -0.94      | -1.42    |
| DIV (mm d⁻¹)   | 0.57     | 0.72       | 0.63     | -0.54    | -0.47      | -0.91    |
| PW (mm)        | -1.15    | -1.04      | -2.00    | -0.10    | -0.10      | -0.17    |
| MSE (L kg⁻¹)   | -689     | -615       | -1095    | PBLH (mm)| 51.2       | 48.9     |
| Trans (mm d⁻¹) | -0.23    | -0.25      | -0.85    |          |            |          |

Rnet: net radiation; HFX: sensible heat fluxes; LH: latent heat fluxes; DIV: water vapor horizontal divergence/convergence (positive indicates enhanced divergence and negative represents enhanced convergence comparing CTRL with FCPL); PW: column precipitable water, MSE: moist static energy; Trans: canopy transpiration; QFX: water vapor vertical fluxes; T2: 2 m air temperature; TPCP: total precipitation, CPCP: convective precipitation; Runoff: surface gridded runoff; PBLH: PBL height.

Convection rainfall (CPCP, see figure 4(i)). The horizontal water flux divergence/convergence (DIV) shows little changes in spatial coverage over the region shown as the box (figure 4(g)); the ozone-damage to plants mainly causes convective rainfall to decrease as also evidenced in comparing total precipitation (TPCP, see figure 4(h)) and CPCP (figure 4(i) and table 1). This process will be intensified since the decrease of rainfall causes a decrease in LH and an increase in HFX and finally an increase in both air temperatures and [O₃] (see figure 3(c)). The consistent decreases of ET (or LH) and precipitation indicate that rainfall changes mainly result from local recycling (Eltahir and Bras 1996, Trenberth 1999).

Comparing figures 4 and S3, although there are relatively high DMA8 [O₃], the effects of COE on hydroclimate are relatively small over arid regions such as the Great Basin (Nevada, Utah), Arizona, southern California, and Mexico, where soil is very dry (Xia et al 2012). In these arid regions vegetation is more constrained by soil water stress than by COE (Nunn et al 2006, Hayes et al 2012, Super et al 2015). As with these western regions, the effects of COE on hydroclimate are small in the eastern US and the Great Lakes since modeled DMA8 [O₃] are low in most of these regions most of the time as shown in figure S3.

Table 1 shows the magnitude of the changes in the box area as shown in figure 4. Although the magnitudes differ among different experiments, the negative/positive trend is the same for the three experiments. The consistent changes show that ozone-damage to plants results in measurable hydroclimate variations simulated. Note that the number shown in table 1 is only counted and averaged in those grid cells that are statistically significant (under 95%-level for Student-t test).

Based on figure 4 and table 1, we learn the following:

1. The changes of model sensible heat fluxes, LH fluxes, and air temperature are consistent with field experiments (e.g. from Bernacchi et al 2011, Van-Loocke et al 2012) and changes of model sensible heat fluxes and LH fluxes are also consistent with offline model studies (e.g., Felzer et al 2009, Lombardozzi et al 2012, 2015);

2. Previous offline model studies (e.g., Felzer et al 2009, Lombardozzi et al 2012, 2015) indicate that ozone damage to vegetation increases surface runoff since ET decreases and soil moisture increases, and consequently runoff increases. In the offline model simulations, meteorological fields such as temperature and precipitation are prescribed. In this study, the FCPL model shows that precipitation decreases (figures 4(h) and (i) and table 1) due to ozone damage to vegetation, and, therefore, surface runoff decreases (table 1), consistent with the results from Sun et al (2012) that are based on observations and statistical model; but inconsistent with the results from Felzer et al (2009) and Lombardozzi et al (2012 and 2015) that are based on offline physical models, indicating the importance of using the FCPL mode.

3.3. Interannual variations and diurnal changes

In this subsection, we present the interannual and diurnal variations of temperature and total precipitation caused by ozone damage to vegetation. Figure 5 presents 2 m air temperature (figure 5(a)) and total precipitation (figure 5(b)) changes year by year. Data in figure 5 are averaged in the box shown in figure 4. Figure 5 shows that the trends of temperature increase and those of precipitation decrease are very consistent in spite of the interannual variations and the differences of experiment setup. The changes of the magnitudes for the same year depend on different experiment setups. For example, the changes of the magnitude for SLOP-O40 and NOSLOP-O40 runs are much smaller (less than 1 °C in temperature and 1 mm d⁻¹ for precipitation) than those from SLOP-O20 run. The changes of the magnitudes for different years may also rely on background meteorological and ozone chemical conditions of the specific years, even in the same experiment setup. For example, for the SLOP-O20 run, temperatures increase from about...
1 °C in the year of 2011 to about 2.5 °C in the years of 2007 and 2010, while precipitation decreases from 0.5 mm d$^{-1}$ in 2008 to about 2.0 mm d$^{-1}$ in 2007. In this study, the emission sources are fixed and no interannual variations are applied. Therefore, the changes of hydroclimate fields to be caused by the effects of ozone damage to plant are influenced by the interannual variations of climate and ozone chemistry.

The rainfall and temperature diurnal variations over the focused area (see the box shown in figure 4 for location) are also examined and shown in figure 6 (see figure S4 for the means). Ozone exposure changes the rainfall and temperature diurnal cycles. In areal average, temperatures increase by 2.5 °C during daytime and 1.5 °C during nighttime for the FCPL-SLOP-O20 run and over 0.6 °C–0.75 °C during daytime and by about 0.3 °C at night for the other two experiment runs. These unequal increases in temperature at different times of the day make the daily temperature range (DTR) increase by 1.0 °C for the SLOP-O20 run and about 0.3 °C–0.4 °C for the other two FCPL runs. The reason is that during daytime, ozone concentrations are high due to maximal photochemical reaction rates while during night ozone concentrations are low due to the lack of sunlight and consumption by VOC and/or NOx.

The rainfall diurnal cycles (figure 6(b)) have two peaks in decrease: one occurs at midnight (about 9 am UTC) and the other occurs in the afternoon (18–20 UTC) with small magnitudes (less than 0.1 mm h$^{-1}$). However, since the total rainfall average is relatively small, the relative changes can reach about 40% for the SLOP-O20 run and about 20% for the other two FCPL runs.

4. Conclusions

In this study, the non-radiative forcing effects of surface chronic ozone exposure (COE) on vegetation’s photosynthesis and leaf stomatal conductance are implemented into WRF/Chem. The modified WRF/Chem is used to investigate regional hydroclimate in the United States in 2007–2012. Three different FCPL

---

**Figure 5.** Changes of 2 m air temperature (a) and total precipitation (b) in different years. Data are averaged over the entire area (shown as the box in figure 4) for June, July, and August, 2007–2012.

**Figure 6.** Changes in the diurnal cycles of temperature (a) and precipitation (b) due to ozone damage to plants. Data are averaged over the entire focused area (shown as the box in figure 4) for June, July and August, 2007–2012.
experiments (SLOP-O40, NOSLOP-O40, SLOP-O20) are designed to add the effects of COE on plant conductance and photosynthesis (PCP) in the WRF/Chem. Two parallel simulations (with/without considering the chronic ozone damage to vegetation) are conducted during the high ozone concentration season (i.e., May–September). The modeled rainfall and 2 m air temperature matched quite well the observations and reanalysis data and are comparable with previous numerical studies. However, the model underestimated precipitation in the central Great Plains and overestimated precipitation in the eastern coastal states and Texas and surrounding regions. The modified model improved precipitation in Texas, New Mexico, and northward to Nebraska compared with the control run and reference data.

COE mainly affects precipitation and temperature in those regions with high ozone concentrations. COE reduces transpiration (and ET) or LH fluxes, hence increases Bowen ratios, and increases surface air temperatures and PBLH heights. Ozone damage to plants weakens convective potential and therefore decreases convective rainfall. In other words, the local recycling of water is responsible for the rainfall decrease. Our simulations and sensitivity studies indicate:

1. Surface air temperatures in Texas and surrounding regions increase by 0.2 °C–2 °C depending on location and experimental setup. Furthermore, the increase of air temperature is greater during daytime than nighttime, resulting in DTR increases of 0.4 °C–1.0 °C for the 6 year average, a new finding.

2. Average rainfall decreases in Texas and surrounding regions by 0.9–1.4 mm d\(^{-1}\) in the analysis periods—June through August. This finding has not been reported previously.

3. Surface runoff decreases with magnitudes from 0.1 to 0.2 mm d\(^{-1}\), corresponding to rainfall decrease in these areas. The result is inconsistent with previous offline process-based model results but is consistent with the results based on observations and statistical models.

Our study indicates that considering the chronic ozone effect in the fully coupled climate model is important for improving temperature and precipitation prediction. In the modified fully coupled system, ozone’s damage to PCP affects not only temperature and rainfall but also surface energy redistributions, planetary boundary-layer dynamics, gross primary product (yield), and ozone photochemistry as well, which will be discussed in a separate paper.

Previous studies indicate that the interactions of CO\(_2\), nutrients, soil water stress, and O\(_3\) are important in investigating O\(_3\) damage effects on vegetation, GPP and hydrology. These phenomena are left for future investigations.

Acknowledgments
This work has been partially supported by NSF grant DMS 1419593, USDA NIFA grant 2015–67003–23508 and NSF EAR grant 1204774. We are grateful to the two reviewers for the comments and suggestions.

References
Ainsworth E, Yendrek C, Stich S, Collins W and Emberson L 2012 The effects of tropospheric ozone on net primary productivity and implications for climate change Annu. Rev. Plant Biol. 63 657–61
Alter R, Fan Y, Lintner B and Weaver C 2015 Observational evidence that Great Plains irrigation has enhanced summer precipitation intensity and totals in the midwestern US J. Hydrometeor. 16 1717–35
Avnery S, Mauzerall D, Liu J and Horowitz L 2011 Global crop yield reductions due to surface ozone exposure: 1. Year of 2000 crop production losses and economic damage Atmos. Environ. 45 2284–96
Bernacchi C, Leakey A, Kimball B and Ort D 2011 Growth of soybean at future tropospheric ozone concentrations decreases canopy evapotranspiration and soil water depletion Environ. Pollut. 150 1464–72
Calatayud V, Cervero J and Sanz M 2007 Foliar, physiological and growth responses of four maple species exposed to ozone Water Air Soil Pollut. 185 239–54
Chen M, Shi W, Xie P, Silva V, Kousky V E, Higgins W and Janowiak J 2008 Assessing objective techniques for gauge-based analyses of global daily precipitation J. Geophys. Res. 113 110
Collins W J, Sitch S and Boucher O 2010 How vegetation impacts affect climate metrics for ozone precursors J. Geophys. Res. 115 D23308
Cowan I and Thoughto J 1971 Relative role of stoma in transpiration and assimilation Plant 97 325–36
Cuchiara G C, Li X, Carcalho J and Rappengluck B 2014 Intercomparison of planetary boundary layer parameterization and its impacts on surface ozone concentrations in the WRF/Chem model for a case study in Houston/Texas Atmos. Environ. 96 175–85
DeAngelis A, Dominguez F, Fan Y, Robock A, Kustu M D and Robinson D 2010 Evidence of enhanced precipitation due to irrigation over the Great Plains of the United States J. Geophys. Res. Atmos. 15 11–14
Eltahir E and Bras R 1996 Precipitation recycling Rev. Geophys. 34 367–78
Emmons L K et al 2010 Description and evaluation of the model for ozone and related chemical tracers, version 4 (MOZART-4) Geosci. Model Dev. 3 43–67
Felzer B, Reilly J, Mellilo J, Kicklighter D, Sarofim M, Wang C, Prim R and Zhuang Q 2007 Future effects of carbon sequestration and climate change policy using a global biogeochemical model Clim. Change 73 345–73
Felzer BS, Cronin T W, Mellilo J M, Kicklighter D W and Schlosser C A 2009 Importance of carbon–nitrogen interactions and ozone on ecosystem hydrology during the 21st century J. Geophys. Res. 114 G01020
Francini A, Nali C, Picchi V and Lorenzini G 2007 Metabolic changes in white clover clones exposed to ozone Environ. Exp. Bot. 60 11–9
Ginoux P, Chin M, Tegen I, Prospero J, Holben B, Dubovik O and Lin S-J 2001 Sources and global distributions of dust aerosols simulated with the GOCART model J. Geophys. Res. 106 20255–73
Grell G and Devenyi D 2002 A generalized approach to parameterizing convection combining ensemble and data assimilation techniques Geophys. Res. Lett. 29 4
Grell G, Peckham S, Schmitz R, McKeeen S, Frost G, Skamarock W and Eder B 2003 Fully coupled ‘online’
Tai A, Val Martin M and Heal C 2014 Threat to future global food security from climate changes and ozone air pollution Nat. Clim. Change 4 817–21
Tao Z, Santanello J, Chin M, Zhou S, Tan Q, Kemp E and Peters-Lidard C 2013 Effect of land cover on atmospheric processes and air quality over the continental United States—a NASA Unified WRF (NU-WRF) model study Atmos. Chem. Phys. 13 6207–26
Tie X, Madronich S, Walters S, Zhang R, Rasch P and Collins W 2003 Effect of clouds on photolysis and oxidants in the troposphere J. Geophys. Res. 108 4642
Tjeolker M, Volin J, Oleksyn J and Reich P 1995 Interaction of ozone pollution and light effects on photosynthesis in a forest canopy experiment Plant Cell Environ. 18 895–905
Trenberth K 1999 Atmospheric moisture recycling: role of advection and local evaporation J. Clim. 12 1368–83
Van Dingenen R, Dentener F, Raes F, Krol M, Emberson L and Cofala J 2009 The global impact of ozone on agricultural crop yields under current and future air quality legislation Atmos. Environ. 43 604–18
VanLoocke A, Betzelberger A, Ainsworth E and Bernacchi C 2012 Rising ozone concentrations decrease soybean evapotranspiration and water use efficiency whilst increasing canopy temperature New Phytol. 195 164–71
Wittig V, E, Ainsworth E A and Long S P 2009 Quantifying the impact of current and future tropospheric ozone on tree biomass, growth, physiology and biochemistry: a quantitative meta-analysis Glob. Change Biol. 15 396–424
Xia Y et al. 2012 Continental-scale water and energy flux analysis and validation for the North American land data assimilation system project phase 2 (NLDAS-2): I. Intercomparison and application of model products J. Geophys. Res. 117 D03109
Yegorova E, Allen D, Loughner C, Pickering K and Dickerson R 2011 Characterization of an eastern US severe air pollution episode using WRF-Chem J. Geophys. Res. 116 D17306
Zhang F, Bei N, Nielsen-Gammon J W, Li G, Zhang R, Stuart A and Aksoy A 2007 Impacts of meteorological uncertainties on ozone pollution predictability estimated through meteorological and photochemical ensemble forecasts J. Geophys. Res. 112 D04304