Predicted impacts of climate and land use change on surface ozone in the Houston, Texas, area

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Received 13 January 2008; revised 16 July 2008; accepted 5 August 2008; published 30 October 2008.

This paper studies the effects of climate change under future A1B scenario and land use change on surface ozone (O\(_3\)) in the greater Houston, Texas, area. We applied the Weather Research and Forecasting Model with Chemistry (WRF/Chem) to the Houston area for August of current (2001–2003) and future (2051–2053) years. The model was forced by downscaled 6-hourly Community Climate System Model (CCSM) version 3 outputs. High-resolution current year land use data from National Land Cover Database (NLCDF) and future year land use distribution based on projected population density for the Houston area were used in the WRF/Chem model coupled with an Urban Canopy Model (UCM). Our simulations show that there is generally a 2°C increase in near-surface temperature over much of the modeling domain due to future climate and land use changes. In the urban area, the effect of climate change alone accounts for an increase of 2.6 ppb in daily maximum 8-h O\(_3\) concentrations, and a 62% increase of urban land use area exerts more influence than does climate change. The combined effect of the two factors on O\(_3\) concentrations can be up to 6.2 ppb. The impacts of climate and land use change on O\(_3\) concentrations differ across the various areas of the domain. The increase in extreme O\(_3\) days can be up to 4–5 days in August, in which land use contributes to 2–3 days’ increase. Additional sensitivity experiments show that the effect of future anthropogenic emissions change is on the same order of those induced by climate and land use change on extreme O\(_3\) days.


1. Introduction

High levels of surface ozone (O\(_3\)), one of major air pollutants in the lower troposphere, have detrimental effects on human health and plants. The conditions conducive to high O\(_3\) concentrations near the surface generally include warm weather, high solar radiation and high-pressure systems. Future continuing increase in the average global temperature as predicted by most climate models, together with future land use change induced by human activities [Intergovernmental Panel on Climate Change (IPCC), 2007] may exert a strong influence on future surface O\(_3\) air quality. It is of primary interest to examine future air quality change in response to future changes in climate and land use, to help policy makers set future national air quality standards such as the National Ambient Air Quality Standard (NAAQS) in the United States.

In recent years, efforts have been put into estimating future changes in surface O\(_3\) concentrations due to changes in future anthropogenic emissions and climate change on global and regional scales [e.g., Prather et al., 2003; Hogrefe et al., 2004; Mickley et al., 2004; Leung and Gustafson, 2005; Forkel and Knoche, 2006; Murazaki and Hess, 2006; Racherla and Adams, 2006; Tao et al., 2007; Tagaris et al., 2007]. Prather et al. [2003] summarized the projected future changes in O\(_3\) on a global scale on the basis of 10 global models. Yet their study only considers changes in O\(_3\) due to changes in anthropogenic emissions. Hogrefe et al. [2004] reported the first study that applied a modeling system consisting of a global climate model, a regional climate model, and an air quality model to estimate the potential effects of future climate change on surface O\(_3\) over the eastern United States. More recently, Tagaris et al. [2007] estimated the impacts of future global climate change and emissions change on U.S. O\(_3\) concentrations; their results revealed that climate change, alone, with no emissions change had a small effect on the maximum 8-h O\(_3\) concentrations. Tao et al. [2007] investigated the relative contributions of projected future emissions change and climate change to surface O\(_3\) concentrations in the United States. The results of their study showed that the magnitude of changes in surface O\(_3\) concentrations differed in metropolitan and rural areas. However, in these studies, future urban land use change in metropolitan areas is not included.
As more land area in metropolitan regions is expected to be converted from natural and vegetated land cover to human-dominated uses in the future, resulting changes in air temperature, wind field, humidity and height of the atmosphere boundary layer induced by land use change [Civerolo et al., 2000; Grossman-Clarke et al., 2005; Liu et al., 2006; Lo et al., 2007] can affect the production and distribution of air pollutants [Taha, 1996; Taha et al., 1998; Civerolo et al., 2007; Wang et al., 2007]. It has been demonstrated that the spatial patterns of air pollutants were positively correlated with urban built-up density [Weng et al., 2006], indicating the requirement of better treatments of urban features in the numerical models. By refining a land use classification for the arid Phoenix metropolitan area and introducing a bulk approach to a mesoscale atmospheric model, Grossman-Clarke et al. [2005] found that the model with the new features can better simulate the daytime part of the diurnal temperature cycle in the urban area, which can improve the simulation of surface O₃ levels in air quality models.

Despite the recognition that land use change can have significant impacts on modeled meteorology and air quality, most of the previous studies generated future regional climate variables to drive the air quality models without any adjustments to the land use patterns [e.g., Hogrefe et al., 2004; Tao et al., 2007]. The exception of work includes Civerolo et al. [2007], who applied future land use data estimated by a land use change model to one climate scenario to explore the effects of increased urbanization on surface O₃. However, in their work, they used global climate model outputs, a regional climate model along with an offline photochemical model. The treatment for urban land use categories in their study was very simple, through assigning several new parameters for three urban land use types which were classified on the basis of vegetation fraction. As detailed Urban Canopy Models (UCMs) have been developed [e.g., Kusaka et al., 2001; Kusaka and Kimura, 2004a, 2004b; Holt and Pullen, 2007], we are able to better understand the contribution of urbanization to changes in near-surface O₃ from the modeling perspective.

Under the Clean Air Act, the Houston–Galveston–Brazoria (HGB) area is classified as an O₃ nonattainment area, which could be attributed to its rapid urban development, extensive sources of anthropogenic emissions, unique land use and land cover patterns, and complex coastal zones. Most of the previous studies have been focused on the impacts of anthropogenic [e.g., Jiang and Fast, 2004; Tao et al., 2004; Fast and Heilman, 2005; Nam et al., 2006] and biogenic emissions [e.g., Byun et al., 2005; Li et al., 2007] and meteorological conditions [e.g., Dabberdt et al., 2004; Zhang et al., 2007] on O₃ formation [Jimenez et al., 2006; Bossioli et al., 2007]. To date, no work has been done to assess the impacts of future climate change and land use change on the surface O₃ over the Houston area. The recent development of a fully coupled land-atmosphere-chemistry model with a detailed UCM allows us to assess the impacts of both climate change and land use change on air quality on regional scales simultaneously. In this study, results are presented for a modeling study aimed at predicting future changes in surface O₃ concentrations over the greater Houston area, taking into account the effects of climate change and land use change. We begin in section 2 with a brief description of the methods used in this study. In section 3, we compare model results with observations for present-day conditions, and discuss the contributions of future climate change and land use change to surface O₃ changes in the Houston area. Additionally, the results of sensitivity simulations concerning the contribution of anthropogenic emissions change to changed surface O₃ over the Houston area are presented.

2. Methodology

2.1. Regional Land-Atmosphere-Chemistry Model

The physically based Weather Research and Forecasting Model [Skamarock et al., 2005] with Chemistry (WRF/Chem) is a new-generation atmosphere-chemistry model developed collaboratively among several groups including the National Center for Atmospheric Research (NCAR) and the National Oceanic and Atmospheric Administration (NOAA) [Grell et al., 2005]. The computations of meteorology and atmospheric chemistry in the WRF/Chem model share the same land surface schemes, time transport schemes, vertical mixing parameterizations, and time steps for transport and vertical mixing. It has been successfully applied for regional air quality studies [e.g., Fast et al., 2006].

Similar to the WRF model, the WRF/Chem model permits the choice between different physics and chemistry options. The following options were applied for the simulations presented here: Grell cumulus scheme [Grell et al., 1994], WSM 5-class microphysics scheme [Hong et al., 2004], Yonsei University Planetary Boundary Layer (PBL) scheme [Hong and Pan, 1996], Simple Cloud Interactive Radiation scheme [Dudhia, 1989] and Rapid Radiative Transfer Model longwave radiation scheme [Mlawer et al., 1997]. The Regional Acid Deposition Model version 2 (RADM2) chemical mechanism [Stockwell et al., 1990] was used to simulate gas phase chemistry. Several previous studies [e.g., Tie et al., 2001; Martin et al., 2003] suggest that the net effect of aerosols over the United States results in only a small decrease in O₃. Therefore, we did not include aerosol-induced changes in photolysis rates. The photolysis frequencies for the 21 photochemical reactions of the gas phase chemistry model are calculated at each grid point according to Madronich [1987].

We used the Noah land surface model (LSM) [Chen and Dudhia, 2001; Ek et al., 2003] coupled with an UCM in the WRF/Chem model. The Noah LSM calculates surface sensible heat flux, latent heat flux, and skin temperature for natural surfaces. The UCM is coupled to the Noah LSM through urban surface fractions [Kusaka et al., 2001; Kusaka and Kimura, 2004a, 2004b]. This WRF/Noah/UCM coupled modeling system [Chen et al., 2004, 2006] calculates the surface fluxes from man-made surfaces and includes the following: (1) 2-D street canyons that are parameterized to represent the effects of urban geometry on urban canyon heat distribution; (2) shadowing from buildings and reflection of radiation in the canopy layer; (3) the canyon orientation and diurnal cycle of the solar azimuth angle; (4) man-made surfaces consisting of eight canyons with different orientations; (5) Inoue’s model for canopy flows [Inoue, 1963]; (6) the multilayer heat equation for the roof, wall, and road interior temperatures; and (7) a very thin bucket model for evaporation and runoff from road surfaces. To run the UCM within the Noah LSM for...
the Houston area, additional parameters such as building height, roughness length, sky view factor and anthropogenic heat for three land use categories (industrial or commercial, low-intensity residential, and high-intensity residential) are included in an additional lookup table. In general, the industrial or commercial land use category has higher building height, roughness length, and anthropogenic heat, and a lower sky view factor. The parameters for the three different urban land use types in the UCM are presented in Table 1. To conduct future year simulations, one problem is the specification of anthropogenic heating in cities. Because of the steady increase in energy consumption and the growth of cities, anthropogenic heating would change significantly in the future. One sensitivity experiment shows that the effect of anthropogenic heating only leads to a 0.6 ppb increase in \( O_3 \), which is not very significant. So in our future year simulations, we applied the same anthropogenic heating rate as in current year simulations.

2.2. Global and Regional Climate Modeling

Current and future year regional climate fields were obtained by downscaling the NCAR Community Climate System Model version 3 (CCSM3) outputs, which have been used for the IPCC Fourth Assessment Report (AR4) [Collins et al., 2006], to the regional scale. The horizontal resolution of CCSM3 is T85 (~1.41°). The greenhouse gas concentrations during the CCSM3 simulation period used in this study follow the IPCC Special Report on Emission Scenarios (SRES) A1B [IPCC, 2001], with increasing trace gases and aerosol concentrations from 2001 until 2050. The A1B scenario is a midline scenario for carbon dioxide emissions increase until around 2050 and then decrease after that. A full analysis of the CCSM3 future climate simulation is described by Meethel et al. [2006]. In this study, we simulated a control period (2001–2003, denoted as “current”) and a future period (2051–2053, denoted as “future”). We prepared high-resolution initial and boundary meteorological conditions by running the WRF model at 12-km modeling domain driven by 6-hourly CCSM outputs with time-varying sea surface temperature and vegetation greenness fraction. Then, the outputs from 12-km runs were used as the inputs for the 4-km WRF/Chem model domain covering southeastern Texas and centered on the Houston metropolitan area. The simulations were performed for August of 2001–2003 and 2051–2053. To minimize the effect of initial conditions, the initial 2-day period (July 30 and July 31) of each simulation was considered as a spin-up period to establish the initial conditions for several atmospheric concentrations of different emission species.

2.3. Land Use and Land Cover Data

The default land use and land cover data used in the WRF/Chem model are based on 1992–1993 USGS data and do not exactly reflect the land surface conditions of 2000s. We thus replaced this USGS data with the new data derived from 2000 Moderate Resolution Imaging Spectroradiometer (MODIS) data [Friedl et al., 2002]. The 1-km MODIS land use and land cover types were classified by the International Geosphere-Biosphere Programme (IGBP), but excluded the permanent wetland and cropland and natural vegetation types. Three new classes of tundra and inland water bodies have been added by the Land Team at the National Centers for Environmental Prediction (NCEP) as an experimental product used here. Hence, there are 21 types of land use and land cover in the MODIS data set. A comparison of the USGS and MODIS data shows that land cover characteristics are different over the southeastern and surrounding areas of the Houston urban center. However, the dominant land cover types over these regions are relatively similar: “Dryland Cropland and Pasture” in the USGS data set, and “Cropland/Grassland Mosaic” in the MODIS data set. The largest difference occurs in the urban areas because of urban expansion. Moreover, to better characterize the present-day urban land use pattern, we incorporated high-resolution (30-m) USGS 2001 National Land Cover Database (NLCD) urban land use data with detailed urban land use classifications (low-intensity residential, high-intensity residential, and industrial or commercial) for the Houston area (Figure 1a).

Table 1. Surface Parameterizations for Each Land Use Category

<table>
<thead>
<tr>
<th>Urban Type</th>
<th>Urban Fraction</th>
<th>Building Height (m)</th>
<th>Roughness Length (m)</th>
<th>Sky View Factor</th>
<th>Volumetric Parameter (m^-1)</th>
<th>Normalized Building Height (m)</th>
<th>Anthropogenic Heat (cal cm^-1 cm^-1)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Industrial or commercial</td>
<td>0.95</td>
<td>10</td>
<td>1</td>
<td>0.48</td>
<td>0.4</td>
<td>0.50</td>
<td>90.0</td>
</tr>
<tr>
<td>High-intensity residential</td>
<td>0.9</td>
<td>7.5</td>
<td>0.75</td>
<td>0.56</td>
<td>0.3</td>
<td>0.40</td>
<td>50.0</td>
</tr>
<tr>
<td>Low-intensity residential</td>
<td>0.5</td>
<td>5</td>
<td>0.5</td>
<td>0.62</td>
<td>0.2</td>
<td>0.30</td>
<td>20.0</td>
</tr>
</tbody>
</table>
Nevertheless, the future land use data used in our simulations at least provides us one possible scenario to study the impacts of future land use change on O$_3$. It should be noted that changes in land surface conditions in other regions are not considered in this study. Figures 1a and 1b show that urban land use area in the modeling domain increases almost by 62% in the future.

2.4. Anthropogenic and Biogenic Emissions

[13] Anthropogenic emissions of gas species for the years 2000 and 2050 are taken from the U.S. EPA’s 1999 National Emissions Inventory (NEI-99, version 3) released in 2003 at a 4-km horizontal resolution (available from http://www.epa.gov/air/data/neidb.html). The emissions are representative of a typical summer day, as derived by temporal allocation factors specific to each source classification code provided by the EPA. This inventory is designed for regional-scale photochemical models of North America that require hourly emissions data for oxides of nitrogen (NO$_x$), volatile organic compounds (VOC), carbon monoxide (CO), sulfur dioxide (SO$_2$), and ammonia (NH$_3$). The emissions are specified into 41 VOCs categories and are assigned a diurnal profile. The distribution of daily averaged nitrogen oxide (NO) emissions over the Houston area highlights the spatial correlation of the NO emissions and the urban land use (Figure 2a). In order to isolate effects of climate change and land use change from effects of anthropogenic emissions on surface O$_3$, the same anthropogenic emissions were applied for current and future year simulations. To examine the sensitivity of future change in surface O$_3$ to future changes in climate, land use, and anthropogenic emissions, future anthropogenic emissions are estimated by multiplying the present emissions by the growth factors for 2050s according to the SRES A1B scenario [Wigley et al., 2002]. We multiplied CO, NO$_x$, VOC, and CH$_4$ by factors of 1.38, 1.55, 2.01, and 1.46, respectively, for the year 2053. A globally uniform CH$_4$ concentration for current year simulations is 1700 ppb and is projected to rise to 2480 ppb by 2050 in the A1B scenario. Concentrations of CO, NO$_x$, and VOC, which are treated on the basis of NEI-99 for current years, are various across the modeling domain in the future scenario. Initial and boundary conditions for the gas-phase variables were based on those of McKeen et al. [2002], and the laterally invariant vertical profiles representing clean background were created from measurements collected onboard previous NASA-sponsored aircraft missions. Adjustments for boundary conditions are applied to the Houston area. In all simulations, the same chemical boundary conditions are used, which could give rise to some uncertainty in the model results.

[14] Biogenic emissions including isoprene, other biogenic volatile organic compounds (BVOCs), and NO$_x$ are very sensitive to changes in temperature and radiation. Emission rates of biogenic compounds at standard temperature and light conditions (Figure 2b) have been assigned to the model grid on the basis of the Biogenic Emissions Inventory System, version 3 (BEIS3), and the Biogenic Emissions Landuse Database, version 3 (BELD3), which provides distributions of 230 vegetation classes at 1-km resolution over North America [Kinnee et al., 1997]. Then, biogenic emissions in all simulations are calculated online using the temperature and light-dependence algorithms from the BEIS3 [Guenther et al., 1995; Geron et al., 1994; Williams et al., 1992].

2.5. Experiment Design

[15] To thoroughly evaluate the impacts, multiyear ensemble simulations would be preferred. However, to run multiyear simulations with this fully coupled atmosphere-chemistry model demands huge amounts of computing time. Under this circumstance, we carefully designed the experiments on the basis of a review of literature and examination of historical O$_3$ data over the Houston. Analysis of 20-year O$_3$ data shows that high O$_3$ episodes frequently occurred in August. Thus, an alternative way to
study the impacts on $O_3$ is to select August to represent the summer season in order to avoid the limitation of computer resources. In previous studies of the impacts of anthropogenic emissions change and climate change on $O_3$ [Hogrefe et al., 2004; Liao et al., 2006; Civerolo et al., 2007; Tao et al., 2007], authors used either one summer season or five consecutive summer seasons for the present and future years to study the impacts. Thereby, we designed our experiments for three consecutive Augusts to represent the present and future scenarios respectively. In future studies, with increasingly available computational resources, multiyear runs would be the optimal way to assess the statistical significance of changes in $O_3$ caused by climate and land use change. Five experiments with different combinations of meteorological conditions, land use and anthropogenic emissions are listed in Table 2. The BASE simulation, which utilized current year land use data, climate conditions, and anthropogenic emissions, is used to assess the model performance and to calculate the predicted changes in the future. Simulations CL, CL-LU, CL-EMIS, and CL-EMIS-LU, with different combinations of future climate, land use, and future anthropogenic emissions, represent future year simulations. Simulations CL-EMIS and CL-EMIS-LU were carried out to understand the potential contribution of future change in anthropogenic emissions to $O_3$ formation in the Houston area in comparison with those of climate change and land use change.

### 3. Results and Discussion

#### 3.1. Evaluation of Simulation Results for Current Year Conditions

The success of the WRF/Chem model simulations was evaluated with a comparison of the model results with surface observations. Since our WRF/Chem simulations were driven by meteorological boundary conditions indirectly from a global climate simulation rather than a simulation of current weather, a direct comparison of the model output with hourly observations is not effective. Instead, the following analysis mainly focuses on an evaluation of the diurnal cycles of simulated monthly averaged daily temperature and $O_3$ concentrations and monthly averaged wind speed, which are very important to correctly simulating air quality sensitivity to climate change or land use change.

Dawson et al. [2007] have examined the sensitivity of $O_3$ concentrations to summertime climate and found that temperature had the largest effect on air-quality standard exceedances, with a 2.5°C temperature increase leading to a 30% increase in the area exceeding the EPA standard. We evaluated the diurnal cycles of monthly averaged 2-m temperature and $O_3$ concentrations and monthly averaged wind speed, which are very important to correctly simulating air quality sensitivity to climate change or land use change.

![Figure 2](image-url) **Figure 2.** (a) Daily average anthropogenic NO emissions in summer (mol km$^{-2}$ hr$^{-1}$) and (b) normalized biogenic emissions of isoprene generated by the BEIS3 (mol km$^{-2}$ hr$^{-1}$). The normalized isoprene emissions are estimated at standard conditions of light, temperature, soil moisture, humidity, and leaf conditions, including a leaf area index of 5, a canopy with 92% mature leaves, a solar angle of 60°, a photosynthetic photon flux density transmission of 0.6, air temperature of 303 K, humidity at 14 g kg$^{-1}$, and soil moisture at 0.3 m$^3$ m$^{-3}$.

### Table 2. List of All Simulations

<table>
<thead>
<tr>
<th>Simulation</th>
<th>Simulation Period</th>
<th>Emissions</th>
<th>Land Use and Land Cover</th>
</tr>
</thead>
<tbody>
<tr>
<td>Base</td>
<td>August 2001–2003</td>
<td>NEI-99 plus BEIS3</td>
<td>MODIS land cover plus NLCD land use</td>
</tr>
<tr>
<td>CL</td>
<td>August 2051–2053</td>
<td>NEI-99 plus BEIS3</td>
<td>MODIS land cover plus NLCD land use</td>
</tr>
<tr>
<td>CL-LU</td>
<td>August 2051–2053</td>
<td>NEI-99 plus BEIS3</td>
<td>MODIS land cover plus future land use</td>
</tr>
<tr>
<td>CL-EMIS</td>
<td>August 2053</td>
<td>future emissions plus BEIS3</td>
<td>MODIS land cover plus NLCD land use</td>
</tr>
<tr>
<td>CL-LU-EMIS</td>
<td>August 2053</td>
<td>future emissions plus BEIS3</td>
<td>MODIS land cover plus future land use</td>
</tr>
</tbody>
</table>

*NEI-99, U.S. EPA’s 1999 National Emissions Inventory; BEIS3, Biogenic Emissions Inventory System, version 3; MODIS, Moderate Resolution Imaging Spectroradiometer; NLCD, National Land Cover Database.*
shows the diurnal evolutions of modeled and measured average 2-m temperature for August 2001–2003. The major pattern of simulated diurnal evolution of temperature is fairly similar to observations, especially during the daytime. The simulated higher nighttime temperature could be related to the uncertainties associated with parameters used in the UCM. As Tokairin et al. [2006] discussed in their work, the urban canopy model with the inclusion of buildings tends to overestimate nighttime temperature over the urban area. Thus, we speculate that the inappropriate building height parameters used in the UCM might lead to this overestimation. The agreement between simulations and measurements in the daytime $\text{O}_3$ concentrations is noteworthy (Figure 4b). However, the model clearly shows a distinct tendency to overpredict $\text{O}_3$ concentrations at night. This discrepancy is a common feature of other three-dimensional chemical transport models [Lamb, 1988; Schere and Wayland, 1989]. Several possible reasons are available to explain the high $\text{O}_3$ bias during the nighttime in the WRF/Chem model. Inaccuracies in the boundary layer dynamics could lead to higher $\text{O}_3$ concentrations. One possibility could be that the bottom model layer is too thick to allow efficient deposition at night. However, there are 30 vertical model layers, with finer vertical resolution in the lower troposphere to allow the model to simulate boundary layer processes more realistically. The bottom model layer is 17 m in all simulations. The depth of the bottom layer does not seem to be a reason causing higher nighttime $\text{O}_3$. After examining the model simulated NO, we found that the model tends to overpredict the OH concentration at low NOx levels [Eisele et al., 1994; McKeen et al., 1997], which can lead to a reduction in the destruction of $\text{O}_3$ at night. In the WRF/Chem simulations, the nighttime NO concentrations are very low, around 0.001 ppb. As a result, we do not focus on nighttime $\text{O}_3$ concentrations in our further analysis, but on the daytime and maximum 8-h $\text{O}_3$ concentrations.

Comparison between the simulated and observed wind speeds (Figure 5) implies that the model has a relatively good performance in terms of simulating surface wind fields over the urban and surrounding regions. The average wind speed over the Houston urban center is around 1.8–2.1 m/s, which is quite close to observations. High wind speed in the south of the urban center is also well captured by the model. We also noticed that the model was able to capture the afternoon sea breeze over the Houston area as reflected by the wind rose pattern for the BASE simulation (as is seen later in Figure 7a). The evaluation of the model performance gives us confidence to examine the future air quality using this coupled model.

3.2. Regional Climate Change

The occurrence of high $\text{O}_3$ concentrations during the summer is strongly determined by meteorological processes within the PBL. We briefly summarize the changes in the meteorological fields over the period between the 2000s and the 2050s on the basis of two simulations: CL-LU, which considers changes in both climate and land use, and BASE. In these simulations, anthropogenic emissions and chemical boundary conditions were fixed at the levels used for the current years, while the calculation of biogenic emissions took into account the effects of temperature and radiation changes under different climates. Meteorological conditions that are known to be associated with high $\text{O}_3$ concentrations are high mixing heights [Rao et al., 2003], low wind speeds, and high temperatures [Ordonez et al., 2005]. Here we discuss details of climate change, particularly those climate variables that are pertinent to $\text{O}_3$ chemistry.

Modeling studies by Sillman and Samson [1995] and Aw and Kleeman [2003] have shown that summertime $\text{O}_3$ concentrations increase as temperature increases. Our model simulates a significant surface temperature rise between 2050s and 2000s. The highest increase in surface temperature during 12–18 LST occurs over the Houston urban area, as indicated by box A (here, we call it “zone A”), with an average increase of 3.3°C (Figure 6a). On average, the surface temperature is predicted to increase by about 2°C. This increase is also clearly apparent in CCSM3 outputs with an increase of 1.5°C in 2-m temperature in most parts of Texas. This is not unexpected, because incorporating a detailed UCM into the regional model at a high spatial
resolution can result in an increase in surface temperature which is somewhat higher than 2-m air temperature during the daytime. Figure 6b also shows that under projected future conditions considering changes in climate and land use, the Houston urban area tends to become drier. Lin et al. [2007] have shown that urban growth tends to decrease the relative humidity because of the increase in urban land surface which has less moisture than vegetated surfaces. Conversely, more water vapor coming from the warming ocean is responsible for higher water vapor mixing ratio along coastal regions. We also noticed that an increase in planetary boundary layer height (PBLH) occurs in the urban areas, with a maximum increase of 250 m and an average increase of 135 m (Figure 6c). As in the work of Civerolo et al. [2007], they suggest that extensive urban growth in the metropolitan area has the potential to increase afternoon near-surface temperature by 0.6°C and increase PBLH by more than 150 m. Here, the patterns in the differences of PBLH and surface temperature are identical. Moreover, under future climate conditions, we also see a daytime decrease in wind speeds with more reduction in the urban center (Figure 6d). The latter is attributed to the increase in roughness length associated with urbanization. The largest decrease of near-surface wind speeds is seen over the urban area (zone A) and southwest of the urban center as indicated by box B (here, we call it “zone B”). The wind direction also changes in response to changes in the distribution of temperature, relative humidity and surface roughness length. An evaluation of the wind rose patterns (Figure 7) indicates that the Houston area has more easterly winds in the afternoon because of future changes in climate and land use for the 2050s. It can be explained that as wind passes
through the urban area, the speed is slowed down because of high roughness length over the extended urban area. More urban land use leads to a decrease of near-surface wind speed in zone B. But it should be pointed out that there is no significant difference in wind speeds in the northwest and northeast of the modeling domain.

3.3. Impact on Regional Distribution of Photooxidants

[21] Future meteorological conditions observed in the simulations are favorable for $O_3$ formation. Increases in surface temperatures, reductions in wind speeds, and changes in boundary layer depths act to change $O_3$ levels through affecting the regional distribution of $O_3$ precursors such as NO$_x$ and VOCs from anthropogenic and biogenic sources.

[22] Figure 8a displays the difference in simulated NO$_x$ mixing ratios between the future and current years (assuming that anthropogenic emissions remain constant). A decrease in near-surface NO$_x$ mixing ratios in the northern part of the Houston urban area and the northwest of the urban center can be attributed to increased PBLH. An increase in NO$_x$ mixing ratio occurs over the southern part of the urban area and along the Bay area, associated with emission sources and decreased PBLH. The oxidation products of NO$_x$, such as nitric acid (HNO$_3$), are dependent on the NO$_x$ concentrations. Figure 8b illustrates an increase in HNO$_3$ in the regions with high NO$_x$ levels, and the highest increase of HNO$_3$ is mainly found along the Bay area and some parts of the urban area. The mixing ratio of peroxyacetyl nitrate (PAN) decreases in the northwest of the modeling domain (Figure 8c), which is mainly due to the increase in temperature that results in an enhanced thermal decomposition of PAN. Apart from the increased temperature, the presence of higher NO$_x$ levels along coastal regions due to emission sources and reduced near-surface wind speeds as shown in Figure 6d favor PAN formation via chemical reactions.

[23] Carbonyl compounds can undergo photochemical reactions that will result in additional production of organic and hydrogen radicals, and produce more $O_3$. As seen in Figure 8d, over much of the modeling domain, formaldehyde (HCHO) increases as temperature increases in the future. This can be explained that the distribution of HCHO strongly depends on isoprene emissions, of which biogenic sources are predominant [Wert et al., 2003]. Under future warm climate conditions, biogenic emissions are expected to increase. The model predicts a 20% increase in biogenic emissions of isoprene in response to future changes in temperature and radiation. It can be seen that the highest increase in HCHO concentrations mostly lies in rural regions, in particular, in the east of the Houston area, where the land surface is mostly covered by forests. Therefore, the significant increase in HCHO is expected to promote additional production of $O_3$ in the areas far from the urban center. However, it should be noted that future change in vegetation types is not considered in this study.

3.4. Changes in Surface $O_3$

[24] The analysis presented in section 3.3 implies that climate and land use change can cause significant changes in predicted concentrations of NO$_x$, HCHO, HNO$_3$, and PAN, which can further affect $O_3$ formation in the Houston area. Figure 9a depicts a spatial map of the difference in $O_3$ concentrations during the afternoon (1200 to 1800 LST) between the future and current year simulations. For the 2050s, changes in summertime average daytime $O_3$ concentrations range from ~2 to 8 ppb. The largest increases of ~4–8 ppb are found over the surrounding regions of the urban center and zone B. However, $O_3$ concentrations are predicted to decrease in the northwest modeling domain. Analysis of model results suggests that this decrease is caused by the decreased water vapor mixing ratio, changed near-surface wind direction (discussed in section 3.2), and the low levels of NO$_x$. Because of more easterly winds in the future, fewer emissions are transported to northwest Houston area from the emission sources. The increased water vapor mixing ratio
Figure 6. Simulated differences in afternoon (1200 to 1800 LST) (a) temperature (°C), (b) 2-m water vapor mixing ratio (kg km⁻¹), (c) planetary boundary layer height (PBLH) (m), and (d) 10-m wind speed (m s⁻¹) between CL-LU and BASE simulations for the month of August (ocean is masked out in all plots). CL-LU represents the future year simulations with the consideration of land use change, and BASE represents the present year simulations.

Figure 7. Simulated wind directions during the afternoon (1200 to 1800 LST) for (a) August 2001–2003 (BASE) and (b) August 2051–2053 (CL-LU).
and decreased wind speeds along the coast, which is closer to the VOC and NO\textsubscript{x} source regions, act to favor the formation of O\textsubscript{3}. In the areas with high PAN levels, the O\textsubscript{3} concentrations are still high [Singh et al., 1985]. We also find increasing isoprene emissions in response to future climate change tend to promote more O\textsubscript{3} formation in the modeling domain. In fact, this result is very sensitive to whether the reaction products of isoprene, isoprene nitrates,

Figure 8. As in Figure 6 but for the differences in (a) NO\textsubscript{x}, (b) HNO\textsubscript{3}, (c) PAN, and (d) HCHO (ppb).

Figure 9. As in Figure 6 but for the differences in (a) O\textsubscript{3} concentrations (ppb) and (b) the number of days with the daily maximum 8-h O\textsubscript{3} concentrations larger than 84 ppb.
represent a terminal or temporary sink for NO\textsubscript{x} [Horowitz et al., 2007]. Wu et al. [2008] found little climate-driven O\textsubscript{3} change in the southeastern United States, and they attributed this to the role isoprene nitrates play as a terminal sink for NO\textsubscript{x}. In this study, we used the RADM2 chemical mechanism which only includes a very simple scheme of isoprene. Thus, the reaction products of isoprene, organic nitrates, are more likely to be a temporary sink for NO\textsubscript{x} in our simulations.

Because the U.S. NAAQS for 8-h O\textsubscript{3} concentration is set at 84 ppb, model-predicted exceedances of this threshold are of particular importance when assessing the effects of climate change and land use change on O\textsubscript{3} air quality. To analyze the changes in the frequency of predicted days with unhealthy O\textsubscript{3} concentrations (referred to as extreme O\textsubscript{3} days hereinafter), the number of days for which the predicted daily maximum 8-h O\textsubscript{3} concentrations exceeded 84 ppb was plotted in Figure 9b. The predicted distribution of the number of days with the maximum daily 8-h O\textsubscript{3} concentrations larger than 84 ppb matches the pattern of increased O\textsubscript{3} over the modeling domain. It can be seen that there is an increase of 4–5 days in the number of days with elevated O\textsubscript{3}, with the largest increase over the surrounding regions of the urban center and zone B. Overall, the WRF/Chem simulations of O\textsubscript{3} concentrations utilizing the WRF downscaled 2050s A1B regional climate fields show an increase in summer average daily maximum 8-h O\textsubscript{3} concentrations and an increase in the number of extreme O\textsubscript{3} days over the Houston area due to future changes in climate and land use.

3.5. Contributions of Climate Change and Land Use Change to O\textsubscript{3} Changes

Sensitivity simulations with the utilization of current and future land use data (CL and CL-LU) are used to discern the contribution of climate change and that of urban land use change to O\textsubscript{3} formation. Figure 10a shows that urban land use change promotes an increase of 1–4 ppb in average afternoon (1200 to 1800 LST) O\textsubscript{3} concentrations over much of the modeling domain in addition to climate change. Moreover, the higher O\textsubscript{3} caused by the land use change is associated with an increase of 1–3 days per month (August) in the number of extreme O\textsubscript{3} days (Figure 10b). The effects of land use change on both O\textsubscript{3} concentrations and extreme O\textsubscript{3} days are the most significant over the surrounding regions of the urban center, but not exactly over the urban center, which is consistent with Civerolo et al.’s [2007] results. In the core urban areas, NO\textsubscript{x} emissions do not contribute to a significant increase in O\textsubscript{3} concentrations, but they do lead to increased O\textsubscript{3} formation in downwind areas. We attribute this increase in the spatial extent of VOC-limited regions to increasing urbanization. To be consistent with the future expansion of urban land use, the VOC-limited regions would be extended correspondingly.

Figure 10. Simulated differences in (a) afternoon (1200 to 1800 LST) O\textsubscript{3} concentrations and (b) the number of days with the daily maximum 8-h O\textsubscript{3} concentrations larger than 84 ppb between CL-LU and CL simulations for the month of August. CL represents the future year simulations using the present year land use data.
lations, daily maximum 8-h O$_3$ concentrations can increase up to 12 ppb in the 2050s (Figure 11c).

[28] We also plotted the frequency distributions of the simulated daily O$_3$ maxima during August over zones A and B. As we expected, because of the future changes in climate and land use, the frequency is shifted toward higher values (Figure 12). It seems that zone B is more likely to be affected by climate change, while zone A displays a pattern highly correlated with the land use change. Climate change alone leads to an increase in days with daily maximum 8-h O$_3$ at 65 ppb in zone B. This results in a significant increase of the number of days with near-surface O$_3$ concentrations higher than 84 ppb in this region, as was discussed above.

[29] The above analysis reveals that the impacts of climate change and land use change on O$_3$ differ across the modeling domain. The contributions of climate change and land use change are illustrated in a bar chart of changes in summertime average daily maximum 8-h O$_3$ concentrations for zones A and B (Figure 13). It can be seen that the effects of climate change alone account for an increase of 2.6 ppb in daily maximum 8-h O$_3$ concentrations in zone A. The land use change has more influence near the urban area than the climate change, with an additional increase of 1 ppb in daily maximum 8-h O$_3$ concentrations. The combined effects of climate and land use change on daily maximum 8-h O$_3$ concentrations can be up to 6.2 ppb. However, in zone B, which is more likely affected by the increased water vapor mixing ratio, reduced wind field and changed wind direction, and increased temperature, the impacts of climate change are stronger than those of future urban land use change.

[30] As discussed above, changes in meteorological variables have different impacts in different locations. To further quantify these impacts, a statistical correlation technique is applied to identify the contributions of different meteorological variables to O$_3$ formation due to climate change and land use change, respectively. A simple regression test was conducted and the correlation coefficients between O$_3$ concentration and these meteorological variables are summarized in Table 3. It is clear that near-surface temperature, wind speed, and humidity are very important meteorological factors influencing the variation in O$_3$ levels in the Houston area. We observed that temperature and water vapor mixing ratio have more influence on O$_3$ concentrations in zone B under future A1B climate scenario, notwithstanding the correlation between O$_3$ concentration and water vapor mixing ratio is negative. When the future land use change is considered in the simulations, the correlation between O$_3$ concentration and PBLH increases, indicating the important impact of land use change on the air quality over the urban areas. To a large extent, the correlation coefficients between temperature or water vapor mixing ratio and O$_3$ concentration are not affected in zone A. However, the coefficients are somewhat different in zone B. This further indicates that zone B is affected by meteorological variables to a larger degree than is zone A.

[31] The analysis above suggests that climate change and land use change have different impacts in different regions. Therefore, while many previous studies have pointed out the potentially important contribution of future climate
change and anthropogenic emissions to O$_3$ air quality for future decades, the results presented here imply that the effects of land use change may be at least equally important to the changing climate when planning for the future attainment of the NAAQS.

### 3.6. Sensitivity of Surface O$_3$ to Future Anthropogenic Emissions

The analysis presented in the previous subsections focused on determining the effects of climate and land use change on summertime O$_3$ concentrations over the Houston area in the absence of changes in anthropogenic emissions within the modeling domain. Several studies have investigated the effects of increasing global and regional emissions on O$_3$ air quality using regional climate and air quality models [Fiore et al., 2002, 2005; Tagaris et al., 2007; Tao et al., 2007]. It is of particular interest to compare the effects of climate and land use change to those caused by change in anthropogenic emissions. For brevity, we only did sensitivity simulations for the year 2053 using the current and future land use data (CL-EMIS and CL-LU-EMIS).

Figure 14 displays the percentage of the number of days in August with the daily maximum 8-h O$_3$ concentrations larger than 84 ppb over the Houston urban area. It can be seen that climate change induces around 8% increase in the extreme O$_3$ days over the urban area. When combined with the land use change, there is an additional 4% increase over the Houston urban area. There are more extreme O$_3$ days under future conditions with the consideration of climate and land use change in zone A than those in zone B. In zone B where the increased O$_3$ concentrations are relatively large, the increase in extreme O$_3$ days is not as significant as that in zone A. The anthropogenic emissions sensitivity experiment shows that the impacts of future change in anthropogenic emissions on extreme O$_3$ days are on the same order of those induced by climate and land use change. Still, zone A is affected more by changes in anthropogenic emissions than is zone B, since the former is a source area for anthropogenic emissions. Therefore the findings presented above may have potentially important implications for policy making concerning population health.

### 4. Conclusions

This paper described the application of a coupled land-atmosphere-chemistry modeling system to understand

![Figure 12](image1.png)

**Figure 12.** Frequency distributions of the simulated daily maximum 8-h O$_3$ concentrations averaged over zone A (dashed lines) and zone B (solid lines) during August for BASE (blue), CL (green), and CL-LU (red) simulations.

![Figure 13](image2.png)

**Figure 13.** Spatially averaged contributions of climate-induced change, land use-induced change, and combined climate and land use change from the 2000s to the 2050s to changes in daily maximum 8-h O$_3$ concentrations.

<table>
<thead>
<tr>
<th>O$_3$</th>
<th>Zone</th>
<th>2-m Temperature</th>
<th>2-m Water Vapor Mixing Ratio</th>
<th>10-m Wind Speed</th>
<th>PBLH*</th>
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<tbody>
<tr>
<td>CL simulations zone A</td>
<td>0.53</td>
<td>-0.63</td>
<td>-0.79</td>
<td>0.19</td>
<td></td>
</tr>
<tr>
<td>CL simulations zone B</td>
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<td>-0.89</td>
<td>-0.62</td>
<td>0.79</td>
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<tr>
<td>CL-LU simulations zone A</td>
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<td>-0.64</td>
<td>-0.69</td>
<td>0.59</td>
<td></td>
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<tr>
<td>CL-LU simulations zone B</td>
<td>0.74</td>
<td>-0.92</td>
<td>-0.65</td>
<td>0.78</td>
<td></td>
</tr>
</tbody>
</table>

*Planetary boundary layer height.

Table 3. Correlation Studies Between O$_3$ Concentrations and the Main Meteorological Variables

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The percentage of the number of days with the daily maximum 8-h O₃ concentrations larger than 84 ppb over zone A and zone B. CL-LU-EMIS represents future year simulations with the consideration of future anthropogenic emissions change.

References


Acknowledgments. This work is supported by the U.S. EPA STAR program (grant RD83145201), the National Center for Atmospheric Research (NCAR) Advanced Study Program, the NCAR FY07 Director Opportunity Fund, and NASA Headquarters under the NASA Earth and Space Science Fellowship Program (grant NNX07AO28H). The NCAR is operated by the University Corporation for Atmospheric Research under sponsorship of the National Science Foundation. We are indebted to the land team at the NCEP for providing us the MODIS land cover data set and to Mukul Tewari for making the current land use data available to us. Shiguang Miao is thanked for helping set up the UCM in the WRF/Chem model. We thank Mary Barth, Xueei Tie, Alex Guenther, Jerome Fast, William Vizuete, Gregory Frost, Steven Peckham, George Grell, Jonathan Plein, Alma Hodzic, Peggy Lemone, and Susanne Grossman-Clarke for their valuable discussions during the course of this work. The computing resources are provided by the Texas Advanced Computing Center.

The percentage of the number of days with the daily maximum 8-h O₃ concentrations larger than 84 ppb over zone A and zone B. CL-LU-EMIS represents future year simulations with the consideration of future anthropogenic emissions change.


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