Title
Future land use and land cover influences on regional biogenic emissions and air quality in the United States

Journal
Atmospheric Environment, 43(36)

ISSN
1352-2310

Authors
Chen, Jack
Avise, Jeremy
Guenther, Alex
et al.

Publication Date
2009-11-01

DOI
10.1016/j.atmosenv.2009.08.015

Atmospheric Environment 43 (2009) 5771–5780

Contents lists available at ScienceDirect

Atmospheric Environment

journal homepage: www.elsevier.com/locate/atmosenv

Future land use and land cover influences on regional biogenic emissions and air quality in the United States

Jack Chen [a,1], Jeremy Avise [a,2], Alex Guenther [b], Christine Wiedinmyer [b], Eric Salathe [c], Robert B. Jackson [d], Brian Lamb [a,*]

[a] Washington State University, Pullman, WA, USA
[b] National Center for Atmospheric Research, Boulder, CO, USA
[c] University of Washington, Seattle, WA, USA
[d] Duke University, Durham, NC, USA

ARTICLE INFO

Article history:
Received 12 March 2009
Received in revised form
4 August 2009
Accepted 5 August 2009

Keywords:
Biogenic emission
Global change
Air quality
Dispersion model
Land use
Land cover
Ozone
Secondary organic aerosol

ABSTRACT

A regional modeling system was applied with inputs from global climate and chemistry models to quantify the effects of global change on future biogenic emissions and their impacts on ozone and biogenic secondary organic aerosols (BSOA) in the US. Biogenic emissions in the future are influenced by projected changes in global and regional climates and by variations in future land use and land cover (LULC). The modeling system was applied for five summer months for the present-day case (1990–1999, Case 1) and three future cases covering 2045–2054. Individual future cases were: present-day LULC (Case 2); projected-future LULC (Case 3); and future LULC with designated regions of tree planting for carbon sequestration (Case 4). Results showed changing future meteorology with present-day LULC (Case 2) increased average isoprene and monoterpene emission rates by 26% and 20% due to higher temperature and solar insolation. However when LULC was changed together with climate (Case 3), predicted isoprene and monoterpene emissions decreased by 52% and 31%, respectively, due primarily to projected cropland expansion. The reduction was less, at 31% and 14% respectively, when future LULC changes were accompanied by regions of tree planting (Case 4). Despite the large decrease in biogenic emission, future average daily maximum 8-h (DM8H) ozone was found to increase between +8 ppbv and +10 ppbv due to high future anthropogenic emissions and global chemistry conditions. Among the future cases, changing LULC resulted in spatially varying future ozone differences of −5 ppbv to +5 ppbv when compared with present-day case. Future BSOA changed directly with the estimated monoterpene emissions. BSOA increased by 8% with current LULC (Case 2) but decreased by 45%–28% due to future LULC changes. Overall, the results demonstrated that on a regional basis, changes in LULC can offset temperature driven increases in biogenic emissions, and, thus, LULC projection is an important factor to consider in the study of future regional air quality.

1. Introduction

Natural emissions such as those from plants are important components of the Earth System that can significantly affect regional air quality. Plants emit large quantities of biogenic volatile organic compounds (BVOC). Annual BVOC emissions in the US significantly exceed the combined total of anthropogenic VOC emissions (Lamb et al., 1993; Geron et al., 1994). Of all the BVOC emitted from plants, isoprene (C_5H_8) is the predominant compound. Isoprene is emitted from many broadleaf trees such as poplar, oak, willow and sycamore. Globally, isoprene represents approximately 44% of the total BVOC emissions, with an estimated annual emission of 390–580 TgC year^{-1} (Guenther et al., 1995; 2006). Isoprene is highly reactive and is an important precursor to ozone (O_3) in the troposphere and has been found to play a role in biogenic secondary organic aerosol (BSOA) production (e.g., Claeys et al., 2004).

Monoterpenes are a group of VOC compounds with two isoprene units ($C_{10}H_{16}$). They are emitted by most coniferous trees. The global emission rate of monoterpenes is approximately 130 TgC year^{-1} (Guenther et al., 1995). Although the global burden of monoterpenes is less than isoprene, their impact on atmospheric chemistry is highly important. Monoterpenes can be oxidized by ozone, hydroxyl radical (OH•) and nitrate radical (NO_3•) to form low vapor pressure products

* Corresponding author at: Washington State University, Department of Civil & Environmental Engineering, 101 Sloan Hall, Spokane Street Pullman, WA 99164-2910, USA. Tel.: +1 509 335 5702.
E-mail address: blamb@wsu.edu (B. Lamb).
[1] Now at: Environment Canada, Ottawa, ON, Canada.
[2] Now at: California Air Resources Board, Sacramento, CA, USA.

1352-2310/$ – see front matter © 2009 Elsevier Ltd. All rights reserved.
doi:10.1016/j.atmosenv.2009.08.015

in the atmosphere. These products readily partition into the aerosol phase and contribute to the formation of BSOA, which can lead to regional haze and reduced visibility (Yu et al., 1999; Kanakidou et al., 2005). A model study by Tsigaridis and Kanakidou (2003) estimated that global BSOA formation from biogenic monoterpene emissions was in the range of 2.5–44.5 Tg year^{-1}. This is more than anthropogenic SOA, which was estimated in the range of 0.05–2.62 Tg year^{-1}. A more recent study suggested the estimates of global atmospheric SOA to be an order of magnitude too low due to insufficient understanding and accounting of atmospheric VOC emissions (Goldstein and Galbally, 2007).

Future global changes including climate change, as well as alterations in land use and land cover (LULC) are factors that can influence future environmental conditions. In order to understand and quantify the impacts of regional air quality from global changes, it is imperative that we account for variations in the magnitude and spatial distribution of the natural emissions. Several studies have examined the global burden of isoprene emissions with respect to global change, and others have investigated the resulting impact on future tropospheric ozone (Wiedinmyer et al., 2006; Hauglustaine et al., 2005; Lathiere et al., 2005; Sanderson et al., 2003). Sanderson et al. (2003) estimated global isoprene emission to increase by 27% in 2090 from the present-day rate of 549 Tg year^{-1} as a result of climate change and the associated natural vegetation distribution. The consequence for air pollution was a 10–20 ppbv increase in global surface ozone. In an alternate scenario where future land cover was unchanged, the study found 34% higher isoprene emissions from the present-day case and even higher ozone levels. Similarly, Wiedinmyer et al. (2006) estimated global isoprene to increase in the future by 70% to 873 TgC year^{-1} with combined climate and LULC changes. This increase in biogenic emissions resulted in higher global surface ozone concentrations with average regional mixing ratios up to 55 ppbv.

The effects of anthropogenic-induced LULC changes such as deforestation and expanding agriculture and urban areas have been shown to impact future global climate and global atmospheric chemistry (Feddema et al., 2005; Foley et al., 2005; Heald et al., 2008). The global effects of LULC changes on biogenic emissions and BSOA was recently examined by Heald et al. (2008). They projected that the global SOA burden to decrease by 14% in 2100 compared to present-day conditions.

In this work, we applied a regional modeling system driven by global models to study the LULC effects on future biogenic isoprene and monoterpene emissions for the continental US. Under the IPCC SRES A2 emissions and climate scenario (IPCC, 2001; Nakićenović and Swart, 2000), we further estimated the impacts on regional ground level ozone and BSOA when combined with projected anthropogenic emission changes in the 2050s. This work follows a decadal simulation study described in Chen et al. (2009) and an attribution study described in Avise et al. (2009).

2. Modeling approach and scenario descriptions

A matrix of four model simulations was constructed to quantify the biogenic emissions and their impacts on ozone and BVOC levels from regional LULC changes. Table 1 outlines the scenarios considered in the study. We recognize that there are other possible scenarios and present these cases as examples to test the sensitivity of regional air quality to potential changes in LULC. The base case (Case 1) represented present-day vegetation distributions and regional environment conditions. Meteorology for this case was from regional climate simulations for the period 1990–1999. Case 2 examined the future biogenic emissions and air quality changes due to global climate changes, without regional LULC adjustments. Case 3 and Case 4 were targeted at the effects of future LULC on biogenic emissions and air quality. Case 3 assumed agriculture as the dominant LULC, and Case 4 assumed regions of tree planting for carbon-sequestration. For consistency, all future simulations (Case 2, 3, 4) were performed with the same future meteorology, future global chemical conditions, and future regional anthropogenic emissions for the period 2045–2054. Additional global changes that can impact future biogenic emissions, such as elevated CO_2, were not examined in this work.

Table 1
Summary of model scenario setup.

	Anthropogenic emission	Meteorology condition	LULC	Remark
Case 1	Current	Current	Current	Present-day base case
Case 2	Future	Future	Current	IPCC A2 with present-day LULC
Case 3	Future	Future	Future	IPCC A2 agriculture LULC
Case 4	Future	Future	Future	IPCC A2 with regional reforestation

The modeling system implemented is similar to that described in Chen et al. (2009). Global climate and chemistry models were coupled to regional meteorology and chemistry models such that results from the global models were used to drive regional simulations. The global models were the NCAR Parallel Climate Model (PCM; Washington et al., 2000), and Model for Ozone and Related Chemical Tracers version 2, (MOZART-2; Horowitz et al., 2003) model. Regionally, the NCAR MM5 meteorological model (Grell et al., 1994) and EPA Community Multi-scale Air Quality model (CMAQ; Byun and Schere, 2006) were used to dynamically downscale the global model outputs to a higher resolution domain (36-km grid) centered over the continental US.

To account for year-to-year weather variability, the modeling system was applied for five different July months in the 1990s, and five July months in the 2050s. Each of the month-long simulations was from continuous meteorological simulations for the 1990–1999 and 2045–2054 periods. Two months were chosen based on modeled maximum and minimum July temperatures, while three additional months were chosen with intermediate July temperatures. The simulations thus covered the range of simulated temperatures, representative of average July conditions of the period, while minimizing the computer resources required for the matrix of runs.

Meteorology for the current decade was modeled without observation assimilations, thus results correspond to present-day conditions with no association to specific events. Climatology and chemical conditions for the future cases were based on the SRES A2 scenario (IPCC, 2001). The A2 storyline represents "business-as-usual" environments. It is one of the worst scenarios with high atmospheric loading of greenhouse gases and ozone precursor emissions (Nakićenović and Swart, 2000).

Regional biogenic emissions for present and future scenarios were generated with the NCAR Model of Emissions of Gases and Aerosols from Nature (MEGAN; Guenther et al., 2006). The model estimates hourly isoprene and other compounds including monoterpenes. The model has detailed characterizations of vegetation distribution, foliar density, leaf energy balance and light attenuation algorithms within a forest canopy. MEGAN vegetation distributions for the present-day cases (Case 1 and Case 2) were based upon satellite observations at 1-km resolution. Vegetation distributions for the future cases (Case 3 and Case 4) were determined from LULC projections as described below. Hourly meteorological fields used in MEGAN were from the MM5 model.

Regional anthropogenic emissions for the US in the base case simulation were from the US EPA 1999 National Emissions Inventory (NEI-1999). For the future scenarios, anthropogenic emissions were projected to 2050s based on emission factors from the US EPA. Future emission changes accounted for projected population and economic growth, but did not include emission reduction policies

or major technological advances affecting future emissions. Spatial distributions of future anthropogenic emissions were updated with population density from the Spatially Explicit Regional Growth Model (SERGOM; Theobald, 2005) to reflect expanding urban areas. On average, anthropogenic VOC, NO_x and CO emissions increased by 50%, 8% and 10%, respectively. Details of the emission changes are available in Chen et al. (2009).

The LULC dataset determines the distribution of vegetation across the US for the prediction of BVOC emissions (Guenther et al., 2006). The future LULC dataset was developed from several sources. Urban areas were defined using SERGOM. Future vegetation and agriculture LULC distributions were based on mappings of plant functional types for the Community Land Model (CLM; Bonan et al., 2002), following the IPCC A2 emissions scenario and the resulting climate conditions. The maps were developed from an interpolation of the Integrated Model to Assess the Global Environment (IMAGE v2.2; Strengers et al., 2004; RIVM, 2002). Natural vegetation in the future was held constant relative to the present-day LULC, while agricultural and grazing land use types were modeled following the IPCC A2 storyline. This scenario for the US is particularly relevant if the updated renewable fuel standard is fully implemented in the Energy Independence and Security Act of 2007. Fig. 1 compares the current and future vegetation coverage for broadleaf trees, needleleaf trees, and croplands. Large decreases in forested areas were estimated in the future. Most notably was the conversion of broadleaf and needleleaf forests to agricultural lands. Significant reductions in forests also occur in the east and coastal Pacific Northwest.

For comparison with the agriculturally dominant future LULC, a second scenario affecting biogenic emissions was examined. The future vegetation distribution was based on the same IPCC A2 storyline, except for regions of managed tree planting in the northern Midwest and southeast. This was aimed at potential greenhouse gas emissions trading by biogenic carbon-sequestration on a large scale, as proposed in offset provisions of cap-and-trade bills before the US Senate and House of Representatives. The scenario followed the study by Jackson et al. (2005). The regions of reforestation were modeled using the Forest and Agriculture Sector Optimization Model-Green House Gases (FASOMGHG) (Adams et al., 1996). The model converted 72 million hectares of non-irrigated agriculture and pasture lands to woody forests driven by carbon trading. Significant portions of the Midwest were forested with hardwood oak and poplar, which have high isoprene emission capacities. Regions in the southeast including areas in Texas, Arkansas, Louisiana, and Mississippi, were forested with pine, which have high monoterpene emission capacities.

3. Results and discussion

3.1. Meteorology

Meteorological variables, including temperature and surface solar insolation, are important factors influencing biogenic emissions. Fig. 2 shows the modeled differences between present-day and future periods for average daily maximum temperature and surface solar insolation. The model estimated higher continental mean temperature by $+2$ °C and higher solar radiation by $+17$ W m^{-2}. Larger temperature increases between $+2$ °C and $+6$ °C were predicted for the northeastern and southwestern US, while smaller increases of between $+1$ °C and $+3$ °C were predicted for the southeastern US. Regions in the Pacific Northwest and the central states had the smallest change. Different spatial distributions were estimated for surface solar radiation. Large increases were estimated in the central states, along the west coast and in southern Florida. These regions were predicted to have higher energy inputs of $+60$ W m^{-2} and $+100$ W m^{-2} due to decreased cloud cover, while states in the east coast were predicted to have lower energy input of -20 W m^{-2} and -60 W m^{-2}. Further analyses of these meteorological changes are discussed in Salathé et al. (2008) and in Avise et al. (2009).

3.2. Biogenic emissions

Fig. 3 shows the isoprene emission rates from the present-day case (plate a) and the changes for the future scenarios (plate b, c, d). In 1990s, elevated isoprene emissions were modeled in the southeast, western California and northern Midwest. A hot spot of >70 mgC m^{-2} day^{-1} in southern Missouri corresponds to the high-density oak forests in the Ozarks region. The average continental isoprene emission rate for the base case was 8 mgC m^{-2} day^{-1} with a standard deviation of 12 mg m^{-2} day^{-1}. This emission estimate was consistent with recent model and measurement studies for present-day summer conditions (Palmer et al., 2006).

In Case 2, the higher future temperatures with current LULC caused average isoprene emissions to increase by 26%. The average continental emission rate was 10 mgC m^{-2} day^{-1} with a standard deviation of 15 mgC m^{-2} day^{-1}. The emission rate increase was proportional to the base case emission rates, such that areas of higher base case isoprene emissions had higher predicted increases. This change was principally due to the overall warmer future temperature across the continent.

In contrast, when future LULC was changed, isoprene emissions were estimated to be lower in both Case 3 and Case 4. Regions of lower emission rates were modeled for the southeast and western California. The southeast region had the largest emission decrease with 26 mgC m^{-2} day^{-1} reductions from about 48 mgC m^{-2} day^{-1} in the base case. Estimated isoprene emissions for Case 4 were similar to Case 3, except for regions of reforestation. The goal of carbon-sequestration through increased poplar and oak plantations increased isoprene emissions by about 4 mgC m^{-2} day^{-1} in the southeast Texas and about 9–26 mgC m^{-2} day^{-1} in the Midwest. The regions of largest increase were Iowa, Illinois and Indiana where reforestation was modeled to take place. Quantitatively, the continental average isoprene emissions for Case 3 and 4 were lower than the base case by 52% and 31%, at 3.8 mgC m^{-2} day^{-1} and 5.4 mgC m^{-2} day^{-1}, respectively, and the emission variability was also lowered, with standard deviation of 6.2 mgC m^{-2} day^{-1} and 8.5 mgC m^{-2} day^{-1}, respectively.

Estimated monoterpene emissions (Fig. 4) showed changes similar to those for isoprene, but at a much lower magnitude, and slightly different spatial distributions. The base case results showed high monoterpenes emission rates for regions in the east, northern Midwest and Pacific Northwest. The high monoterpene emissions in the base case correspond to a high-density of coniferous trees in the area. The continental average monoterpene emission for Case 1 was 2.6 mgC m^{-2} day^{-1} with standard deviation of 4.2 mgC m^{-2} day^{-1}.

Large differences in monoterpene emissions were predicted for future scenarios. Changing climate without LULC changes in Case 2 resulted in 20% higher monoterpene emissions. The continental average emission was 3.2 mgC m^{-2} day^{-1} with standard deviations of 5.1 mgC m^{-2} day^{-1}. The increases were larger for the southeast due to higher base case emissions and higher future temperature.

Changes in future vegetation in Case 3 and Case 4 altered the monoterpene emission rates and spatial distribution. In Case 3, decreases in forested areas reduced monoterpene emissions rate by 2–10 mgC m^{-2} day^{-1}. In Case 4, monoterpene emissions increased across the Midwest, as well as in places in the south and southeast. For the areas of reforestation, there were approximately five fold increases in emission rate, to 25 mgC m^{-2} day^{-1}. However, the continent average monoterpene emission rates for Case 3 and Case 4 decreased by 31% and 14% to 1.8 mgC m^{-2} day^{-1} and 2.3 mgC m^{-2} day^{-1}, respectively; the standard deviation were lower at 2.4 mgC m^{-2} day^{-1} and 2.8 mgC m^{-2} day^{-1}, respectively.

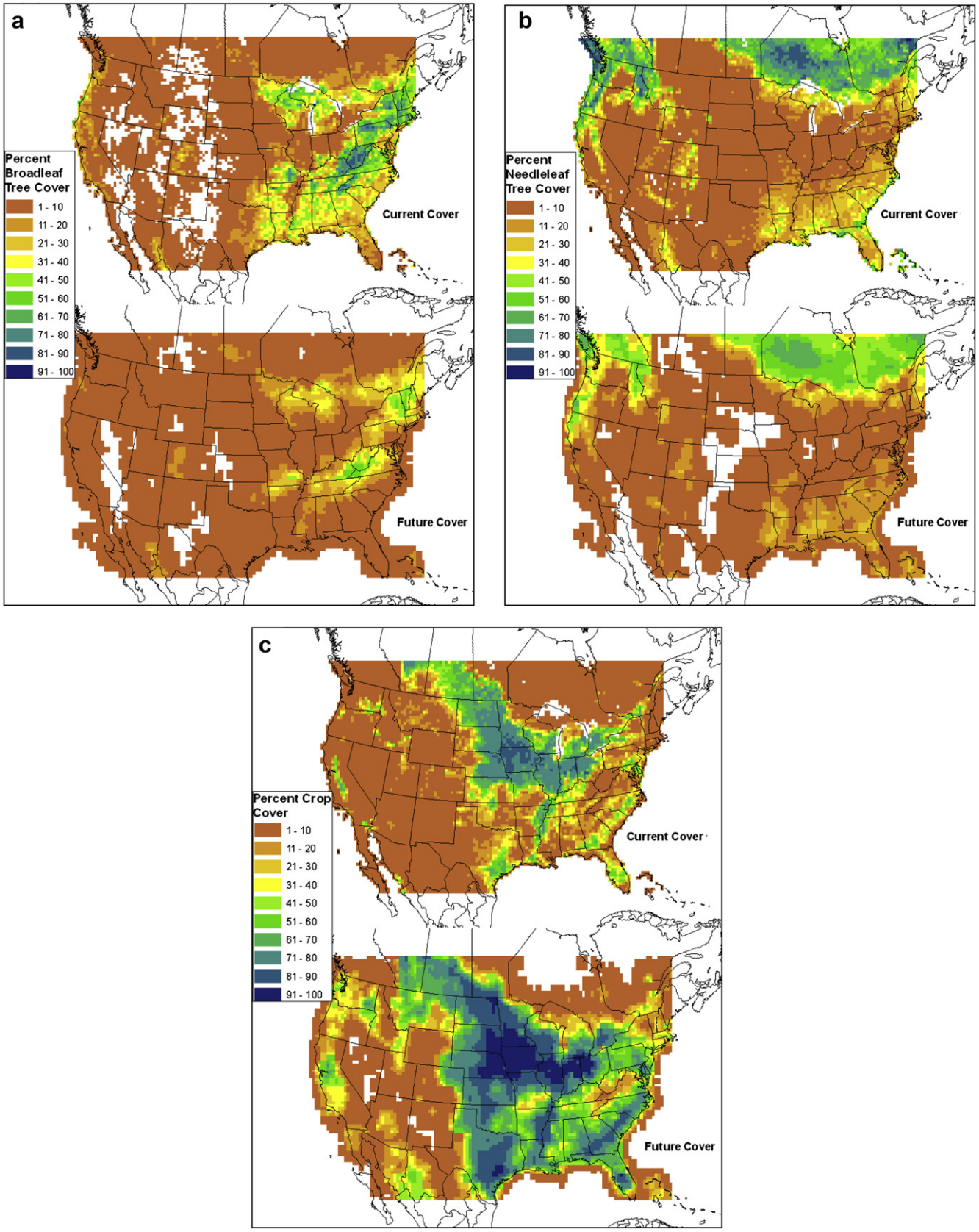

Fig. 1. Estimated percent land cover for current (top) and future (bottom) scenarios for (a) broadleaf trees, (b) needleleaf trees and (c) cropland. This figure is available in color in the online issue.

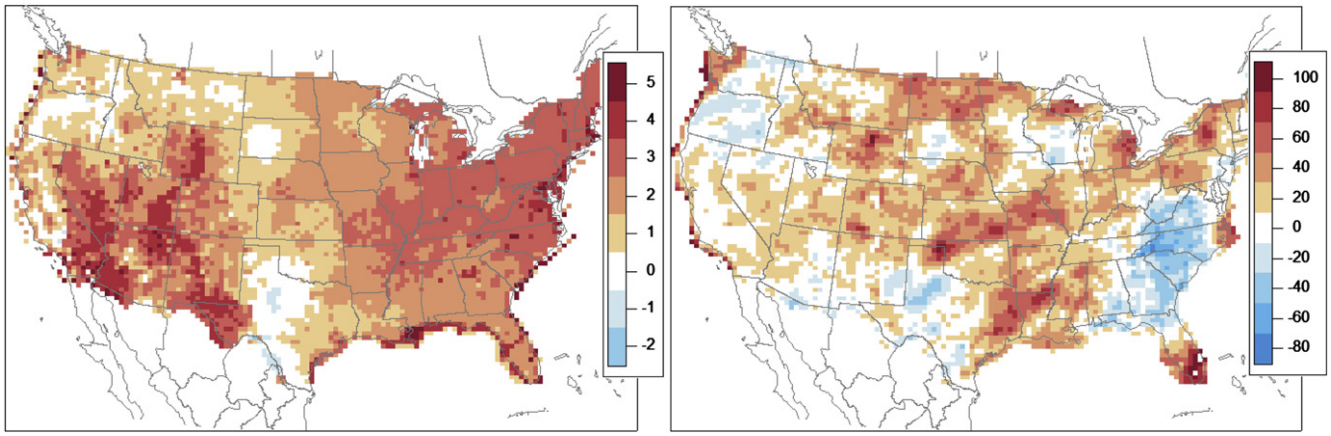

Fig. 2. Modeled future changes for (left) mean daily maximum surface temperature (°C) and (right) mean daily maximum surface solar radiation (W m^{-2}). This figure is available in color in the online issue.

Changing vegetation distributions also changed the spatio-temporal variability of emissions across the continent. Fig. 5 shows the total isoprene and monoterpene emission ranges across the continent for the four cases. The variability comes from changes in daily meteorological conditions across the five July simulations.

In the base case (Case 1), total isoprene emission rates varied from 44 Gg day^{-1} to 92 GgC day^{-1} with average emission of 66 Gg day^{-1}. Monoterpene emission rates varied from 15 GgC day^{-1} to 28 GgC day^{-1} with average of 22 GgC day^{-1}. For the future cases, Case 2 had the highest average emissions, and largest emission variability. Changing future climate without LULC changes increased

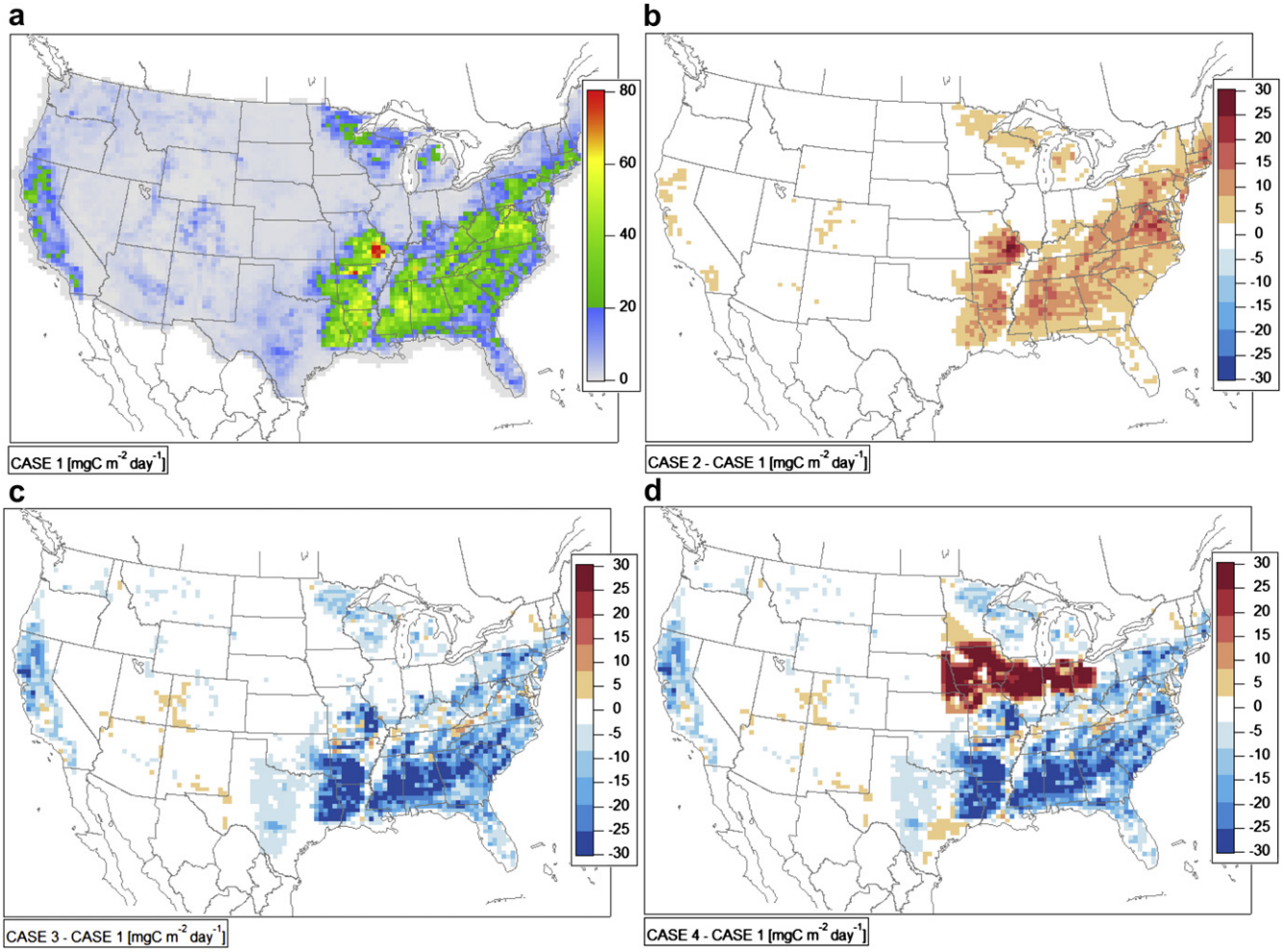

Fig. 3. Mean isoprene emission rate for the present-day case (plate a) and difference plots for the future minus present-day case (plate b, c and d). This figure is available in color in the online issue.

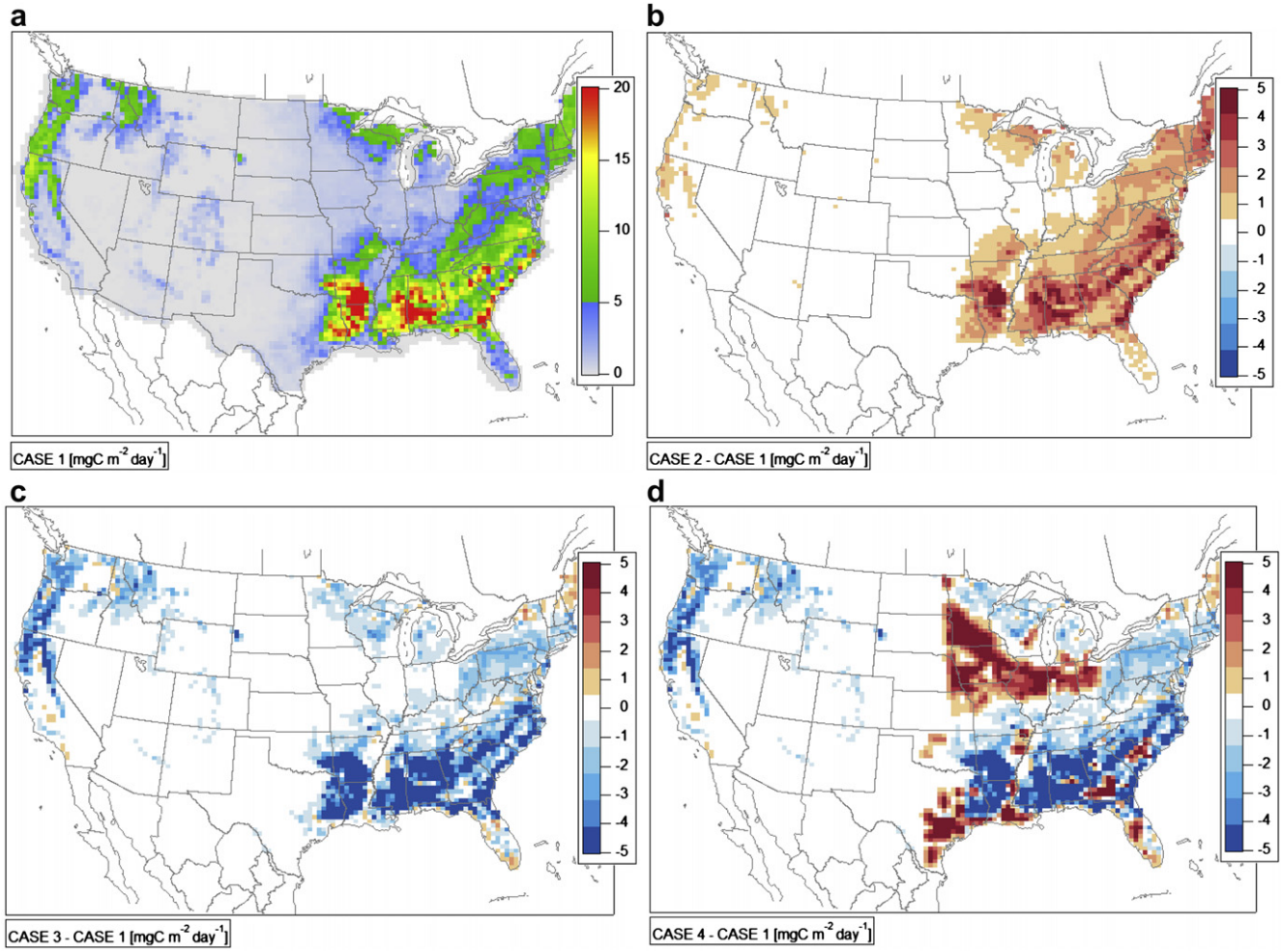

Fig. 4. Mean monoterpene emission rate for the present-day case (plate a) and difference plots for the future minus present-day case (plate b, c and d). This figure is available in color in the online issue.

the base emissions, and widened the temporal emission variability. However, when LULC changed towards an agriculture dominant scenario, both isoprene and monoterpenes emission rates decreased despite the increases in future temperature.

3.3. Future regional air quality implications

Ground level ozone and fine particulate matter (PM) are atmospheric pollutants detrimental to human health and the environment. Biogenic emissions can influence regional air quality via secondary chemical reactions in the atmosphere. Recent studies show future increases in temperature to cause poorer air quality in the US as a result of higher biogenic emissions (Racherla and Adams, 2008; Hogrefe et al., 2004). In this work, ozone and BSOA for the four cases were modeled with scenario-specific anthropogenic emissions as outlined in Table 1.

3.3.1. Ground level ozone

CMAQ predicted higher ozone mixing ratios in all three future cases despite variations in modeled biogenic emissions. The average daily maximum 8-hr (DM8H) ozone for the future cases were between +8 ppbv and +10 ppbv higher compared to the present-day base case (Case 1). This was principally due to the combined effects of future global changes, which include warmer temperature, higher projected anthropogenic emissions, and higher global pollutant background concentrations. As demonstrated in a separate sensitivity study, future global pollution background conditions showed the largest impact on average DM8H ozone in the US (Avise et al., 2009).

Among the future cases, the average DM8H ozone mixing ratios were higher in Case 2 with present-day LULC compared to Case 3 or Case 4. Case 2 with the highest BVOC emissions had more areas with DM8H ozone increases between +20 ppbv and +25 ppbv. These areas were mostly near urban centers in southern California, southeast Texas and along the east coast. Similar results have been demonstrated in other studies where higher biogenic emissions enhanced the future regional ozone production (Racherla and Adams, 2008; Hogrefe et al., 2004; Avise et al., 2009). For Case 3 and 4, the magnitudes of ozone increases were slightly less, due to reductions in BVOC emissions from the LULC changes. Between Case 3 and Case 4, ozone changes were very similar except for regions of reforestation.

There were considerable spatial differences in ozone between the future cases. Fig. 6 shows the average DM8H ozone difference of Case 3 and Case 4 from that in Case 2. Overall, changing LULC in the future lowered the estimated regional ozone. In Case 3, the average DM8H ozone decreased between 1 ppbv and 5 ppbv. There were higher reductions in the eastern US and in California, where LULC changes were most pronounced. The continent average DM8H ozone decreased by 2% with the agriculturally dominant LULC scenario

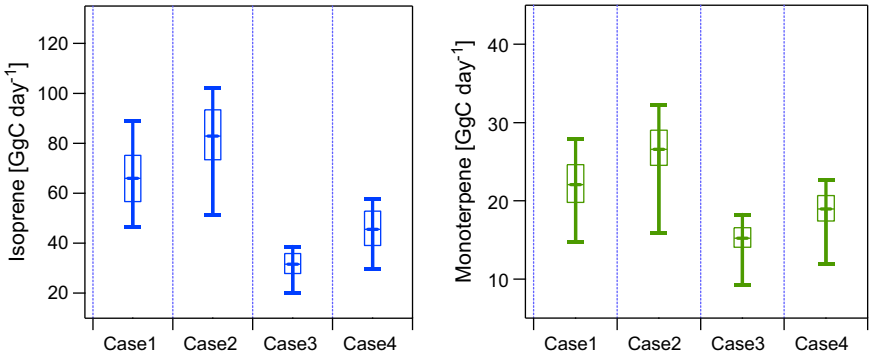

Fig. 5. Mean continent isoprene (left) and monoterpene (right) emission rates. The top and bottom whiskers are maximum and minimum values, respectively, and the box indicates 80th and 20th percentiles with the overall mean in the middle.

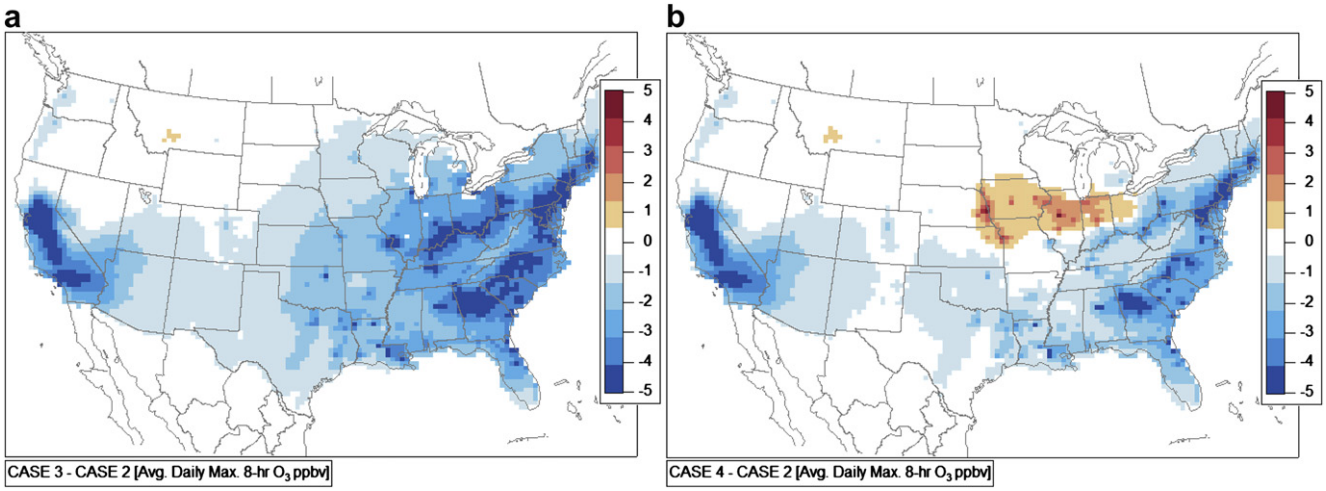

Fig. 6. Average daily maximum 8-hr (DM8H) ozone mixing ratio differences between Case 3 and Case 2 (plate a), and Case 4 and Case 2 (plate b). This figure is available in color in the online issue.

compared with Case 2. In Case 4, the reforested region with higher BVOC emissions in Iowa, Illinois and Indiana caused average DM8H ozone to be distinctly higher. Future average DM8H ozone in these areas increased between +1 ppbv and +5 ppbv. The continent average DM8H ozone decreased by 1% in Case 4 compared to Case 2.

To further evaluate the ozone differences, Fig. 7 shows the ozone spatial distribution variability for the four scenarios. The functions represent percentage areas within the continent where DM8H ozone mixing ratios were greater than the values on the *x*-axis. For the US national ambient air quality standards of 75 ppbv, ~9% of the continental areas exceed this level in Case 1. Among the three future cases, Case 2 had the highest percent area exceeding the threshold (29%). Changes were more minimal for Case 3 and Case 4, at 28% and 27%, respectively. Future global changes together with regional emission changes increased the estimated future ozone, as well as overall area experiencing poorer air quality. The poorer air quality conditions in the future were slightly mitigated by the lower biogenic emissions due to changes in regional LULC.

3.3.2. *Biogenic secondary organic aerosol*

The CMAQ secondary organic aerosol science algorithm follows the approach of Schell et al. (2001). The model simulates secondary organic aerosol as function of VOC oxidation from ozone, $OH^{\bullet}$ and $NO_3^{\bullet}$ radicals. In the model's aerosol module, the BSOA precursor gas-phase compound is primarily monoterpenes. Although many studies have demonstrated BSOA production from isoprene and

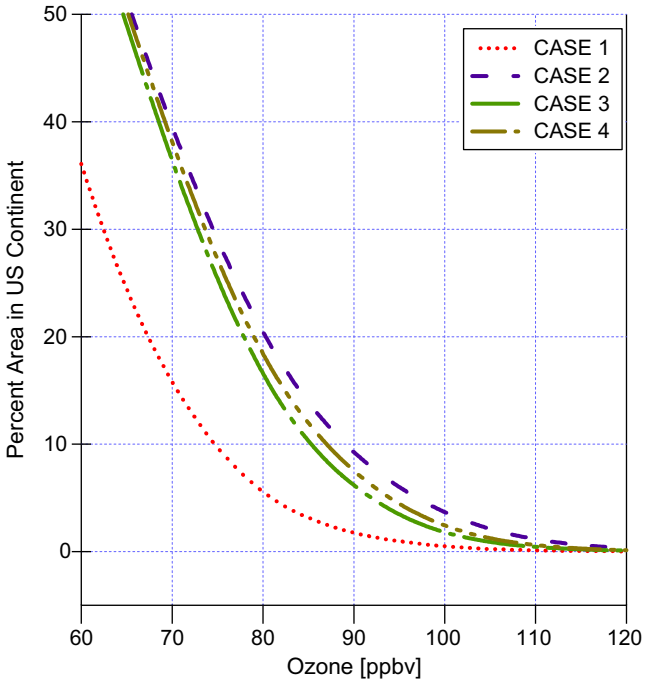

Fig. 7. Percent area cumulative distribution of daily maximum 8-hr (DM8H) ozone mixing ratio.

sesquiterpene oxidations (Claeys et al., 2004; Vizuete et al., 2004; Kroll et al., 2005, 2006), the model used in this study does not include these mechanisms. The results here, therefore, represent minimum bounds on BSOA burden from future changes in biogenic emissions.

Fig. 8 shows the 24-hr average BSOA concentrations for the base case (plate a) and the concentration changes for the future cases (plate b, c, d). Elevated BSOA were estimated for regions with high monoterpene emissions in the east, northern Midwest, and Pacific Northwest. The present-day summer peak continental BSOA concentrations of approximately 2.5 μg m^{-3} occurred in the southeast near Atlanta, GA and Birmingham, AL. The model also estimated high BSOA along the Pacific Northwest with average concentrations ranging from 0.5 μg m^{-3} to 1.5 μg m^{-3}. Across the continent, the average BSOA was 0.5 μg m^{-3}.

BSOA concentrations varied directly to the changes in future biogenic monoterpene emissions. Case 2 with highest continental monoterpene emissions and predicted future ozone had the highest overall BSOA concentrations. Under present-day LULC, the mean continental 24-hr BSOA increased by 8%. Large increases happened in the east and Pacific Northwest. BSOA increases ranged from +0.2 μg m^{-3} to +0.9 μg m^{-3}. There were areas in the southeast and coastal Pacific where BSOA decreased with respect to Case 1. This is largely due to reductions in atmospheric oxidant OH• levels from increases in future regional emissions, thus resulting in decreased BSOA production at night.

When LULC was changed with predicted future climate in Case 3 and Case 4, BSOA concentrations changed by both magnitude and spatial distribution. In Case 3, the reduction in biogenic monoterpenes caused BSOA concentrations to decrease in the southeast and Pacific Northwest. The largest changes occurred in Mississippi, Alabama and Georgia where BSOA reduced by up to 0.9 μg m^{-3}. Averaged across the continent, the modeled 24-hr BSOA decreased by 45%.

In Case 4, the estimated BSOA increased with reforestation. The increases in broadleaf plantations in the Midwest and southeastern Texas increased future BSOA. The increases ranged from +0.2 μg m^{-3} to +0.8 μg m^{-3} compared to the present-day simulation. The mean continental BSOA concentration in Case 4 decreased by 28% compared to the present-day condition. This is an increase of 31% from Case 3 as a result of future reforestation.

Spatial distributions of BSOA for the four cases were slightly different, but follow the changes in estimated monoterpene emissions. Fig. 9 shows the percent area that modeled average 24-hr BSOA concentrations exceed a threshold level. Compared to ozone, the modeled BSOA is highly sensitive to the LULC scenarios despite the changes in meteorology and global chemical conditions. Case 1 and 2 with present-day LULC had more areas with higher BSOA concentrations compared to Case 3 and 4 with projected LULC changes. For a BSOA concentration threshold of 1 μg m^{-3}, Case 1 had 11% of continental area exceeding the threshold, compared to 12% in Case 2; 4% in Case 3; and 5% in Case 4.

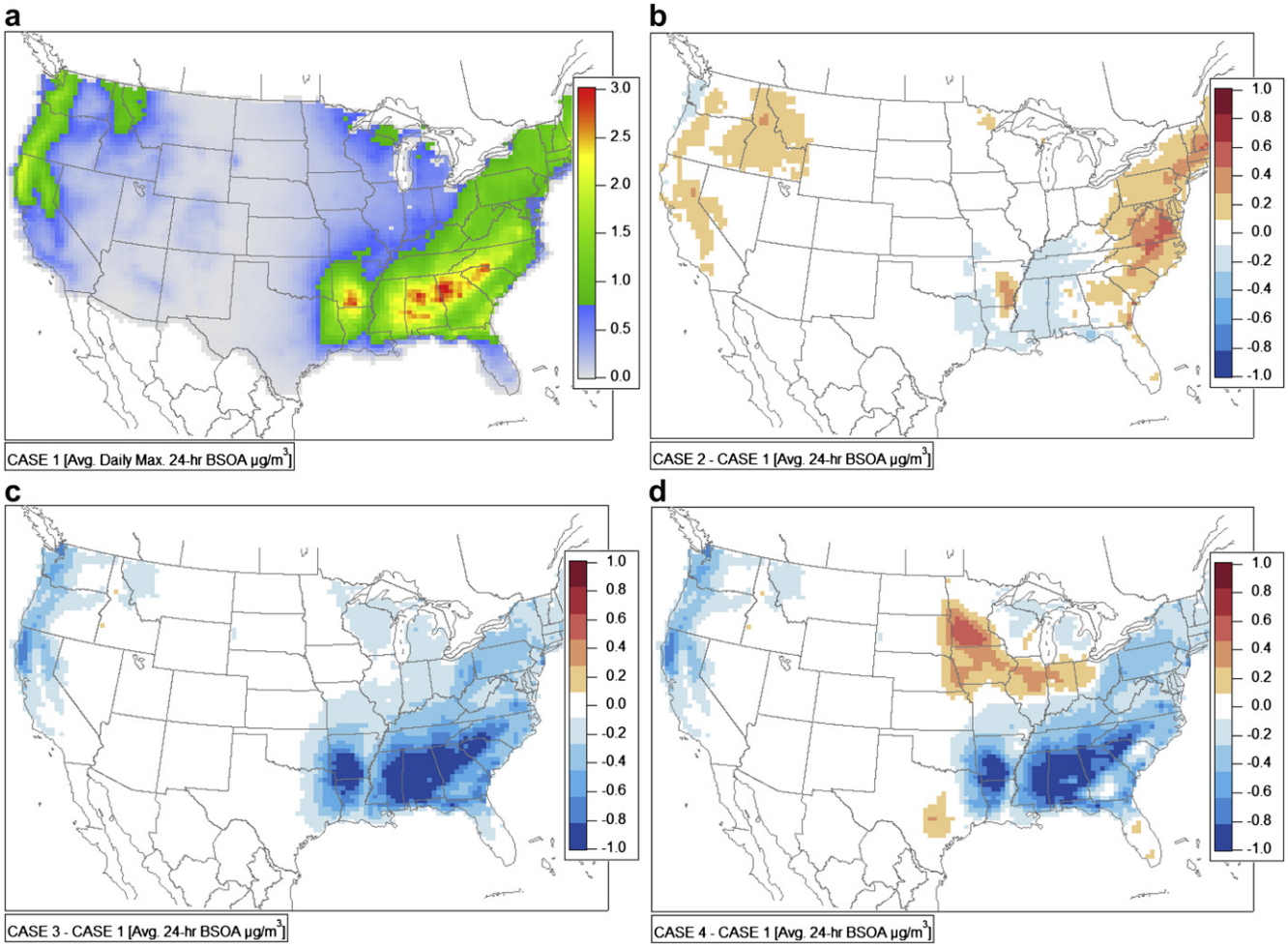

Fig. 8. Average 24-hr BSOA concentrations for the present-day case (plate a) and difference plots for the future minus present-day case (plate b, c and d). This figure is available in color in the online issue.

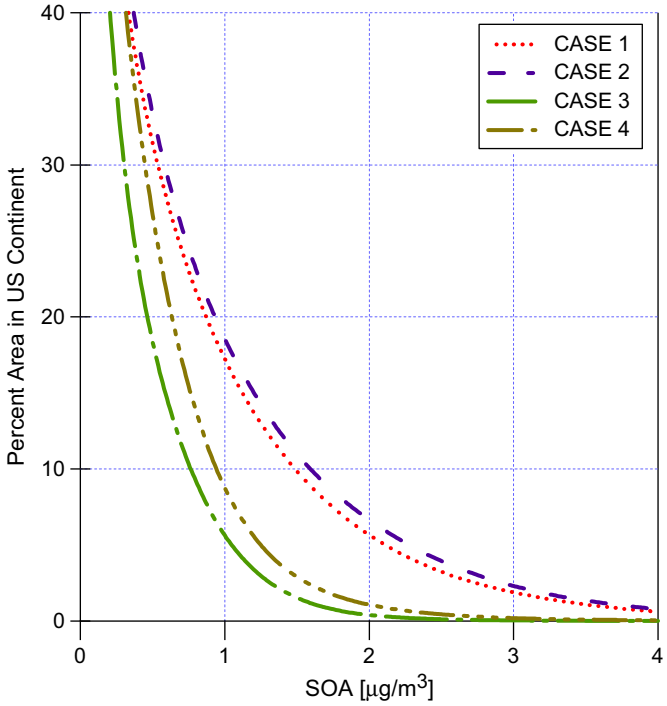

Fig. 9. Percent area cumulative distribution of 24-h biogenic secondary organic aerosol (BSOA) concentration.

4. Summary and conclusions

We have applied a regional scale modeling system driven by global models to quantify the effects of future LULC on biogenic emissions and to examine the impact on future ozone and BSOA in the US. A matrix of four model simulations was completed (Table 1). Future anthropogenic influences followed the IPCC SRES A2 business-as-usual storyline. The cases considered changes in global climate, global pollution concentrations, and US regional anthropogenic emissions. BVOC response to future increases in CO_2 concentrations were not considered in these scenarios. Three regional LULC scenarios considered for the future cases were: present-day LULC, agriculture-dominant LULC, and agriculture-dominant LULC with regions of managed tree planting.

Changes in regional LULC showed large impacts towards future biogenic isoprene and monoterpene emissions. Warmer temperature and higher solar insolation in the future increased biogenic emissions; however, when regional LULC changes were considered, the estimated reductions in forest vegetation significantly decreased BVOC by even larger amount. Changing LULC reduced the future biogenic emission magnitudes as well as the spatiotemporal distributions of biogenic emissions throughout the continent.

In simulations of the future, when LULC was unchanged from present-day conditions, the effects of warmer climate caused average continental isoprene and monoterpene emission rates to increase by 26% and 20%, respectively.

When LULC were allowed to change, the agriculturally dominant LULC caused average isoprene and monoterpene emission rates to decrease by 52% and 31%, respectively, despite the warmer future climate. In the case of reforestation in designated regions, the emission reductions were slightly less at 31% and 14%, respectively. Managed forest expansions increased isoprene and monoterpene emissions. In addition to overall emission differences, changing LULC also altered the emission temporal and spatial variability. Large regions of homogeneous vegetation in the future reduced the spatial variability of emissions regardless of future climate.

In terms of future regional air quality, continental-average DM8H ozone was estimated to increase. Among the three future scenarios, present-day LULC resulted in the highest regional ozone due to higher biogenic emissions. However, for the cases with LULC changes, the continental-average DM8H ozone was slightly mitigated by the reductions in biogenic emissions. Future BSOA concentrations varied directly with the estimated future biogenic monoterpene emissions. When LULC was unchanged, high monoterpene emissions caused average BSOA to increase by 8% across the continent. However, when LULC were allowed to change, the agriculture dominant scenario lowered BSOA concentration by 45%, and the reforestation scenario showed 28% reductions. Since the model did not consider the effects of BSOA from isoprene and sesquiterpene, the results presented in this study represent lower sensitivity bounds towards biogenic emission changes.

The results from this work highlight the sensitivity and uncertainty of model scenarios for future regional biogenic emissions and air quality conditions. Changes in future global environments are expected to cause variations in weather, which in turn can change ecosystems, plant physiology and behavior, and result in shifts in natural vegetation. Anthropogenic interactions, including urban expansion, agriculture intensification, and fire management can further alter the natural landscapes. These accumulated LULC changes can have direct consequences on future atmospheric chemistry. Additional factors, including the response of isoprene emission to elevated CO_2, can have additional impacts on biogenic emissions. These changes and the associated uncertainties are important factors to consider in the studies of future air quality.

Acknowledgment

This work was supported by the EPA STAR Program (RD-83096201) and for JRB the National Institute for Climate Change Research of the US Department of Energy (DOE). The authors would like to thank D. Theobald (Colorado State University) for SERGOM data, J. Feddema (University of Kansas) for LULC dataset, J-F. Lamarques (NCAR) for MOZART-2 results, and L. Buja and G. Strand (NCAR) for PCM results. The Parallel Climate Model project was supported by the US Department of Energy's Office of Biological and Environmental Research and the National Science Foundation Directorate for Geosciences NCAR is operated by the University Corporation for Atmospheric Research under sponsorship of the NFS.

References

Adams, D.M., Alig, R.J., Callaway, J.M., McCarl, B.A., Winnett, S.M., 1996. The Forest and Agricultural Sector Optimization Model (FASOM): Model Structure and Policy Applications. USDA Forest Service Research Paper, PNW-495. Pacific Northwest Research Station, Portland, Oregon.

Avise, J., Chen, J., Lamb, B., Wiedinmyer, C., Guenther, A., Salathé, E., Mass, C., 2009. Attribution of projected changes in summertime US ozone and $PM_{2.5}$ concentrations to global changes. Atmos. Chem. Phys. 9, 1111–1124.

Byun, D.W., Schere, K.L., 2006. Review of the governing equations, computational algorithms, and other components of the models-3 Community Multiscale Air Quality (CMAQ) modeling system. Appl. Mech. Rev. 55, 51–77.

Bonan, G.B., Oleson, K.W., Vertenstein, M., Levis, S., Zeng, X.B., Dai, Y.J., Dickinson, R.E., Yang, Z.L., 2002. The land surface climatology of the community land model coupled to the NCAR community climate model. J. Clim. 15 (22), 3123–3149.

Chen, J., Avise, J., Lamb, B., Salathé, E., Mass, C., Guenther, A., Wiedinmyer, C., Lamarque, J.-F., O'Neill, S., McKenzie, D., Larkin, N., 2009. The effects of global changes upon regional ozone pollution in the United States. Atmos. Chem. Phys. 9, 1125–1141.

Claeys, M., Graham, B., Vas, G., Wang, W., Vermeylen, R., Pashynska, V., Cafmeyer, J., Guyon, P., Andreae, M.O., Artaxo, P., Maenhaut, W., 2004. Formation of secondary organic aerosols through photooxidation of isoprene. Science 303 (5661), 1173–1176.

Feddema, J.J., Oleson, K.W., Bonan, G.B., Mearns, L.O., Buja, L.E., Meehl, G.A., Washington, W.M., 2005. The importance of land-cover change in simulating future climates. Science 310 (5754), 1674–1678.

Foley, J.A., DeFries, R., Asner, G.P., Barford, C., Bonan, G., Carpenter, S.R., Chapin, F.S., Coe, M.T., Daily, G.C., Gibbs, H.K., Helkowski, J.H., Holloway, T., Howard, E.A.,

Kucharik, C.J., Monfreda, C., Patz, J.A., Prentice, I.C., Ramankutty, N., Snyder, P.K., 2005. Global consequences of land use. Science 309 (5734), 570–574.

Geron, C.D., Guenther, A.B., Pierce, T.E., 1994. An improved model for estimating emissions of volatile organic compounds from forests in the eastern United States. J. Geophys. Res. 99 (D6), 12773–12791.

Goldstein, A.H., Galbally, I.E., 2007. Known and unexplored organic constituents in the earth's atmosphere. Environ. Sci. Technol. 41 (5), 1514–1521.

Grell, A.G., Dudhia, J., Stauffer, D.R., 1994. A Description of the Fifth-generation Penn State/NCAR Mesoscale Model (MM5). NCAR Technical Note NCAR/TN-398+STR. National Center for Atmospheric Research.

Guenther, A., Hewitt, C.N., Erickson, D., Fall, R., Geron, C., Graedel, T., Harley, P., Klinger, L., Lerdau, M., Mckay, W.A., Pierce, T., Scholes, B., Steinbrecher, R., Tallamraju, R., Taylor, J., Zimmerman, P., 1995. A global-model of natural volatile organic-compound emissions. J. Geophys. Res. 100 (D5), 8873–8892.

Guenther, A., Karl, T., Harley, P., Wiedinmyer, C., Palmer, P.I., Geron, C., 2006. Estimates of global terrestrial isoprene emissions using MEGAN (Model of Emissions of Gases and Aerosols from Nature). Atmos. Chem. Phys., 6107–6173.

Hauglustaine, D.A., Lathiere, J., Szopa, S., Folberth, G.A., 2005. Future tropospheric ozone simulated with a climate-chemistry-biosphere model. Geophys. Res. Lett. 32 (24). doi:10.1029/2005GL024031.

Heald, C.L., Henze, D.K., Horowitz, L.W., Feddema, J., Lamarque, J.-F., Guenther, A., Hess, P.G., Vitt, F., Seinfield, J.H., Goldstein, A.H., Fung, I., 2008. Predicted change in global secondary organic aerosol concentrations in response to future climate, emissions, and land use change. J. Geophys. Res. 113, D05211. doi:10.1029/2007JD009092.

Hogrefe, C., Lynn, B., Civerolo, K., Ku, J.Y., Rosenthal, J., Rosenzweig, C., Goldberg, R., Gaffin, S., Knowlton, K., Kinney, P.L., 2004. Simulating changes in regional air pollution over the Eastern United States due to changes in global and regional climate and emissions. J. Geophys. Res. 109 (D22). doi:10.1029/2004JD004690.

Horowitz, L.W., Walters, S., Mauzerall, D.L., Emmons, L.K., Rasch, P.J., Granier, C., Tie, X.X., Lamarque, J.F., Schultz, M.G., Tyndall, G.S., Orlando, J.J., Brasseur, G.P., 2003. A global simulation of tropospheric ozone and related tracers: description and evaluation of MOZART, version 2. J. Geophys. Res. 108 (D24). doi:10.1029/2002JD002853.

Intergovernmental Panel on Climate Change (IPCC), 2001. Atmospheric chemistry and greenhouse gases. In: Houghton, J.T., Ding, Y., Griggs, D.J., et al. (Eds.), Climate Change 2001: The Scientific Basis. Cambridge Univ. Press, New York, pp. 229–288.

Jackson, R.B., Jobbagy, E.G., Avissar, R., Roy, S.B., Barrett, D.J., Cook, C.W., Farley, K.A., Le Maitre, D.C., Mccarl, B.A., Murray, B.C., 2005. Trading water for carbon with biological carbon sequestration. Science 310 (5756), 1944–1947.

Kanakidou, M., Seinfeld, J.H., Pandis, S.N., Barnes, I., Dentener, F.J., Facchini, M.C., Van Dingenen, R., Ervens, B., Nenes, A., Nielsen, C.J., Swietlicki, E., Putaud, J.P., Balkanski, Y., Fuzzi, S., Horth, J., Moortgat, G.K., Winterhalter, R., Myhre, C.E.L., Tsigaridis, K., Vignati, E., Stephanou, E.G., Wilson, J., 2005. Organic aerosol and global climate modelling: a review. Atmos. Chem. Phys. 5, 1053–1123.

Kroll, J.H., Ng, N.L., Murphy, S.M., Flangan, R.C., Seinfield, J.H., 2005. Secondary organic aerosol formation from isoprene photooxidation under high NO_x. Geophys. Res. Lett. 32, L18808. doi:10.1029/2005GL023637.

Kroll, J.H., Ng, N.L., Murphy, S.M., Flangan, R.C., Seinfield, J.H., 2006. Secondary organic aerosol formation from isoprene photooxidation. Environ. Sci. Technol. 40 (6), 1869–1877.

Lamb, B., Gay, D., Westberg, H., Pierce, T., 1993. A biogenic hydrocarbon emission inventory for the USA using a simple forest canopy model. Atmos. Environ. Part A 27 (11), 1673–1690.

Lathiere, J., Hauglustaine, D.A., De Noblet-Ducoudre, N., Krinner, G., Folberth, G.A., 2005. Past and future changes in biogenic volatile organic compound emissions simulated with a global dynamic vegetation model. Geophys. Res. Lett. 32 (20). doi:10.1029/2005GL024164.

Nakićenović, N., Swart, R. (Eds.), 2000. IPCC Special Report on Emissions Scenarios. Cambridge University Press, New York, USA, p. 570.

Palmer, P.I., Abbot, D.S., Fu, T.M., Jacob, D.J., Chance, K., Kurosu, T.P., Guenther, A., Wiedinmyer, C., Stanton, J.C., Pilling, M.J., Pressley, S.N., Lamb, B., Sumner, A.L., 2006. Quantifying the seasonal and interannual variability of North American isoprene emissions using satellite observations of the formaldehyde column. J. Geophys. Res. 111, D12315. doi:10.1029/2005JD006689.

Racherla, P.N., Adams, P.J., 2008. The response of surface ozone to climate change over the Eastern United States. Atmos. Chem. Phys. 8, 871–885.

RIVM (Rijks Instituut voor Volksgezondheid en Milieu), 2002. IMAGE 2.2 CD release and documentation. The IMAGE 2.2 implementation of the SRES scenarios: a comprehensive analysis of emissions, climate change and impacts in the 21st century, online available at: http://www.rivm.nl/image.

Salathé, E.P., Steed, R., Mass, C.F., Zahn, P., 2008. A high-resolution climate model for the U.S. Pacific Northwest: Mesoscale feedbacks and local responses to climate change. J. Climate 21 (21), 5708–5726. doi:10.1175/2008JCLI2090.1.

Sanderson, M.G., Jones, C.D., Collins, W.J., Johnson, C.E., Derwent, R.G., 2003. Effect of climate change on isoprene emissions and surface ozone levels. Geophys. Res. Lett. 30 (18). doi:10.1029/2003GL017642.

Schell, B., Ackermann, I.J., Hass, H., Binkowski, F.S., Ebel, A., 2001. Modeling the formation of secondary organic aerosol within a comprehensive air quality model system. J. Geophys. Res. 106 (D22), 28275–28293.

Strengers, B., Leemans, R., Eickhout, B., de Vries, B., Bouwman, L., 2004. The land-use projections and resulting emissions in the IPCC SRES scenarios as simulated by the IMAGE 2.2 model. GeoJournal 61 (4), 381–393.

Theobald, D.M., 2005. Landscape patterns of exurban growth in the USA from 1980 to 2020. Eco. Soc. 10 (1) also [online]. http://www.ecologyandsociety.org/vol10/iss1/art32/.

Tsigaridis, K., Kanakidou, M., 2003. Global modelling of secondary organic aerosol in the troposphere: a sensitivity analysis. Atmos. Chem. Phys. 3, 1849–1869.

Vizuete, W., Junquera, V., Allen, D.T., 2004. Sesquiterpene emissions and secondary organic aerosol formation potentials for Southeast Texas. Aero. Sci. Technol. 38, 167–181.

Washington, W.M., Weatherly, J.W., Meehl, G.A., Semtner, A.J., Bettge, T.W., Craig, A.P., Strand, W.G., Arblaster, J., Wayland, V.B., James, R., Zhang, Y., 2000. Parallel Climate Model (PCM) control and transient simulations. Clim. Dyn. 16 (10–11), 755–774.

Wiedinmyer, C., Tie, X.X., Guenther, A., Neilson, R., Granier, C., 2006. Future changes in biogenic isoprene emissions: how might they affect regional and global atmospheric chemistry? Earth Interact. 10. doi:10.1175/EI174.1.

Yu, J., Griffin, R.J., Cocker III, D.R., Flagan, R.C., Seinfeld, J.H., Blanchard, P., 1999. Observation of gaseous and particulate products of monoterpene oxidation in forest atmospheres. Geophys. Res. Lett. 26 (8), 1145–1148.