Atmospheric Environment 120 (2015) 217–226

Contents lists available at ScienceDirect

Atmospheric Environment

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

Forest-atmosphere BVOC exchange in diverse and structurally complex canopies: 1-D modeling of a mid-successional forest in northern Michigan

Alexander M. Bryan [a, *, 1], Susan J. Cheng [b], Kirsti Ashworth [a], Alex B. Guenther [c], Brady S. Hardiman [d], Gil Bohrer [e], Allison L. Steiner [a]

[a] Department of Atmospheric, Oceanic, and Space Sciences, University of Michigan, Ann Arbor, MI 48109, USA
[b] Department of Ecology and Evolutionary Biology, University of Michigan, Ann Arbor, MI 48109, USA
[c] Pacific Northwest National Laboratory, Atmospheric Sciences and Global Change Division, Richland, WA 99352, USA
[d] Department of Earth and the Environment, Boston University, Boston, MA 02215, USA
[e] Department of Civil, Environmental, and Geodetic Engineering, The Ohio State University, Columbus, OH 43210, USA

HIGHLIGHTS

- Canopy structural heterogeneity on BVOC chemistry is assessed using a 1-D model.
- Uniform and variable vertical foliage compositions are compared.
- Heterogeneous canopy emits 34% more isoprene at one AmeriFlux site.
- Alterations in BVOC environment from succession are greater in heterogeneous canopy.

ARTICLE INFO

Article history:
Received 16 February 2015
Received in revised form
27 August 2015
Accepted 28 August 2015
Available online 1 September 2015

Keywords:
Biogenic volatile organic compounds
Canopy modeling
Mixed forests
Forest succession
Tropospheric chemistry

ABSTRACT

Foliar emissions of biogenic volatile organic compounds (BVOC)—important precursors of tropospheric ozone and secondary organic aerosols—vary widely by vegetation type. Modeling studies to date typically represent the canopy as a single dominant tree type or a blend of tree types, yet many forests are diverse with trees of varying height. To assess the sensitivity of biogenic emissions to tree height variation, we compare two 1-D canopy model simulations in which BVOC emission potentials are homogeneous or heterogeneous with canopy depth. The heterogeneous canopy emulates the mid-successional forest at the University of Michigan Biological Station (UMBS). In this case, high-isoprene-emitting foliage (e.g., aspen and oak) is constrained to the upper canopy, where higher sunlight availability increases the light-dependent isoprene emission, leading to 34% more isoprene and its oxidation products as compared to the homogeneous simulation. Isoprene declines from aspen mortality are 10% larger when heterogeneity is considered. Overall, our results highlight the importance of adequately representing complexities of forest canopy structure when simulating light-dependent BVOC emissions and chemistry.

Published by Elsevier Ltd.

1. Introduction

Forest ecosystems influence tropospheric chemistry and climate by releasing volatile organic compounds (VOC), which are key ingredients for ground-level ozone (O_3, Logan, 1985) and secondary organic aerosols (SOA, Claeys et al., 2004). An estimated 90% of global atmospheric VOC derive from biogenic sources (Guenther et al., 2006), yet the magnitude of biogenic VOC (BVOC) emissions is still highly uncertain due to the complexity of emissions and chemistry in forested environments (Di Carlo et al., 2004; Lelieveld et al., 2008; Ganzeveld et al., 2008; Bryan and Steiner, 2013).

Past research often attributes challenges simulating BVOC

* Corresponding author.
E-mail address: ambrya@umich.edu (A.M. Bryan).
[1] Present address: DOI Northeast Climate Science Center, University of Massachusetts, 233 Morrill Science Center, 611 N. Pleasant St., Amherst 01003, USA.

http://dx.doi.org/10.1016/j.atmosenv.2015.08.094
1352-2310/Published by Elsevier Ltd.

chemistry in rural environments to inadequate knowledge of oxidant sources and reaction pathways. In particular, chemistry models can underestimate oxidant concentrations (e.g., the hydroxyl radical, OH) in forests (Tan et al., 2001). Some studies suspect a missing reactive VOC in such environments (Di Carlo et al., 2004), while others propose that additional reaction pathways recycle OH (Lelieveld et al., 2008; Hofzumahaus et al., 2009; Paulot et al., 2009; Peeters et al., 2009) or that OH measurements are overestimated (Mao et al., 2012). In addition to oxidant discrepancies, VOC oxidation products, such as methacrolein and methyl vinyl ketone (MACR + MVK) are poorly simulated, potentially due to insufficient dry deposition (Pugh et al., 2010) or errors in chemical mechanisms (Karl et al., 2009). A recent study suggests that in-instrument MACR + MVK production may lead to measurement overestimations (Rivera-Rios et al., 2014). Additionally, inadequate representation of in-canopy turbulent mixing may account for poorly simulated BVOC chemistry (Bryan et al., 2012).

One additional source of uncertainty in forest chemistry modeling is how the representation of mixed forests, where tree types differ in height (i.e., “canopy heterogeneity”), affects BVOC chemistry simulations. Canopy heterogeneity has important implications for BVOC emissions as emissions depend strongly on light and leaf temperature (Guenther et al., 1993), both of which vary with canopy depth due to shading by leaves and branches, and different tree types emit different types and amounts of VOCs. Isoprene (C_5H_8) is predominantly released in large quantities by broadleaf vegetation, whereas monoterpenes ($C_{10}H_{16}$) derive mostly from needle-leaf vegetation in smaller amounts (Steiner and Goldstein, 2007). Isoprene is one of the primary precursors of tropospheric ozone, whereas isoprene and monoterpenes are important in the formation of SOA (Claeys et al., 2004; Kroll and Seinfeld, 2008). Kiendler-Scharr et al. (2009) found that isoprene may suppress new particle formation; however, many recent field and laboratory studies observed substantial concentrations of isoprene-derived SOA (Brégonzio-Rozier et al., 2015). Most forest-atmosphere models represent forest canopies as vertically homogeneous in foliage type and BVOC emissions despite resolving multiple canopy layers (Pierce and Waldruff, 1991; Lamb et al., 1993; Geron et al., 1994; Guenther et al., 1995; Forkel et al., 2006; Guenther et al., 2006, 2012; Boy et al., 2011). Wolfe and Thornton (2011) simulate distinct understory and overstory BVOC emissions in Blodgett Forest with the Chemistry of Atmosphere-Forest Exchange (CAFE) model; however, the importance of heterogeneity is not assessed. Given the diversity of most forests, neglecting canopy heterogeneity could impact regional atmospheric chemistry.

To assess the importance of canopy heterogenity on BVOC chemistry, we compare a homogeneous and heterogeneous emission distribution with the one-dimensional Canopy Atmospheric Chemistry Emissions model (CACHE, Forkel et al., 2006). Emission distributions are constructed from crown structure measurements at the University of Michigan Biological Station (UMBS), where young pine, oak, and maple are replacing mature aspen and birch, as shown by research from the Forest Accelerated Succession Experiment (FASET, Nave et al., 2011; Gough et al., 2013). Additionally, we examine the impact of canopy heterogeneity on projections of BVOC chemistry following successional mortality by comparing the homogeneous and heterogeneous simulations with aspen and birch included and excluded. Section 2 describes the study region, measurements, model setup, and simulations. Section 3 compares the homogeneous and heterogeneous canopy simulation results for the present-day mid-successional forest and a late-successional forest. A summary and concluding remarks are given in Section 4.

2. Methods

2.1. Site and measurement description

UMBS is located at the temperate-boreal forest transition zone at the northern tip of Michigan's lower peninsula (Schmid et al., 2003), with a diverse array of broad- and needle-leaf vegetation. There are seven dominant tree types, including a mature 23-m high upper canopy of bigtooth aspen (*Populus grandidentata*), quaking aspen (*Populus tremuloides*), and paper birch (*Betula papyrifera*), and a young lower canopy of Eastern white pine (*Pinus strobus*), red maple (*Acer rubrum*), and American Beech (*Fagus grandifolia*). Red oak (*Quercus rubra*) is present in both the upper and lower canopy (Gough et al., 2013). Aspen and oak contribute over 90% of the isoprene at UMBS (Westberg et al., 2001), whereas pine and maple primarily emit monoterpenes, resulting in a highly segregated canopy with predominantly isoprene emissions in the upper canopy and monoterpene emissions in the lower.

We use several sets of measurements from trees located around the UMBS AmeriFlux tower (Table 1, see Section 2.3). Crown base height (h_t, signifying trunk height, i.e., distance from the ground to the first branch containing foliage) and diameter at breast height (DBH) were measured in July 2012 for 248 trees (44 *F. grandifolia*, 23 *Q. rubra*, 1 *P. tremuloides*, and 45 of each of the other four main species) within a 60-m-radius census plot around the AmeriFlux tower. Crown top height (h_c) was estimated from the DBH measurements using allometric relationships following Garrity et al. (2012). These relationships were developed for each of the seven dominant tree species using tree height and DBH measurements collected in 1997 for over 6000 trees within 1 km of the tower (Fig. 1). We applied the mean DBH measurements obtained in 2012 to these allometric relationships derived from the 1997 data to calculate h_c for each species. Leaf area index (LAI) for each tree species was calculated by dividing its canopy-integrated dry mass (m_{dry}, measured from 20 litter traps within the 60-m plot in 2011) by its specific leaf mass (SLM, i.e., the mass of a single leaf divided by its area). A conversion factor of 2.56 (1 mm^2 projected leaf area = total leaf area of 2.56 mm^2) was applied to *P. strobus*, yielding an LAI of 0.717 m^2 m^{-2}, to account for the cylindrical geometry of needle leaves (Perterer and Körner, 1990).

Several measurements from the 2009 Community Atmosphere–Biosphere Interactions Experiment (CABINEX 2009, Bryan et al., 2012) campaign (1 Jul – 8 Aug 2009) at UMBS were used to constrain the model. Measurements were taken from the Program for Research on Oxidants: Photochemistry, Emissions, and Transport (PROPHET, Carroll et al., 2001) tower, located ~400 m southwest of the AmeriFlux tower. Total (direct and diffuse) shortwave (visible and near-infrared) solar radiation, measured at 32.6 m, provide input for the model radiation, which drives surface heating, photochemistry, and the light-dependent BVOC emissions. A second sensor measured solar irradiance at 2 m from Jul 1–21 and at 20.4 m from Jul 21–Aug 8, and is used to evaluate the modeled canopy extinction. 20.4 m air temperature is also used in the BVOC emission parameterization to account for the influence of long-term temperature history on emissions. Turbulent fluxes were measured in the upper canopy (20.4 m) and above the canopy (34 m) using 3-D ultrasonic anemometers, and used to adjust the modeled turbulent exchange (Bryan et al., 2012).

2.2. Model description

CACHE is a 1-D vertical column model with a high-resolution canopy designed to simulate in- and above-canopy concentrations and vertical fluxes of heat and trace gases. CACHE simulates four main processes (Bryan and Steiner, 2013): (1) emissions of