Atmospheric Environment 84 (2014) 314–322

Contents lists available at ScienceDirect

Atmospheric Environment

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

Observed and modeled ecosystem isoprene fluxes from an oak-dominated temperate forest and the influence of drought stress

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HIGHLIGHTS

- We report the highest ecosystem isoprene emission for a temperate deciduous forest.
- A model adequately captured most variations in isoprene emissions.
- Previous temperature and light regimes had significant influence on emissions.
- Drought stress had a complex impact that was not captured by the model.

ARTICLE INFO

Article history:
Received 16 July 2013
Received in revised form
21 November 2013
Accepted 23 November 2013

Keywords:
Biosphere–atmosphere interactions
Isoprene
Eddy covariance
Ecosystem fluxes
Drought stress

ABSTRACT

Ecosystem fluxes of isoprene emissions were measured during the majority of the 2011 growing season at the University of Missouri's Baskett Wildlife Research and Education Area in central Missouri, USA (38.7° N, 92.2° W). This broadleaf deciduous forest is typical of forests common in the Ozarks region of the central United States. The goal of the isoprene flux measurements was to test our understanding of the controls on isoprene emission from the hourly to the seasonal timescale using a state-of-the-art emission model, MEGAN (Model of Emissions of Gases and Aerosols from Nature). Isoprene emission rates from the forest were very high with a maximum of 53.3 mg m^{-2} h^{-1} (217 nmol m^{-2} s^{-1}), which to our knowledge exceeds all other reports of canopy-scale isoprene emission. The fluxes showed a clear dependence on the previous temperature and light regimes, which was successfully captured by the existing algorithms in MEGAN. During a period of drought, MEGAN was unable to reproduce the time-dependent response of isoprene emission to water stress. Overall, the performance of MEGAN was robust and could explain 90% of the observed variance in the measured fluxes, but the response of isoprene emission to drought stress is a major source of uncertainty.

1. Introduction

Isoprene, a biogenic volatile organic compound emitted by certain plant species, is chemically reactive in the atmosphere. The oxidation of isoprene in the atmosphere affects both the production of tropospheric ozone (Trainer et al., 1987) and secondary aerosol formation (Andreae and Crutzen, 1997). Because emission rates depend on environmental conditions (Monson and Fall, 1989), isoprene production by plants is an important biosphere–atmosphere interaction that has implications for regional air quality and global climate change. Ecosystem isoprene emissions can be modeled with algorithms developed from leaf-level observations of emissions that are driven by temperature and light (referred to as G93, Guenther et al., 1993) and have mechanistic underpinnings (Monson et al., 2012). The models use a multi-layer canopy and meteorological conditions as inputs (for example, Guenther et al., 2012). Defining global plant functional types and assigning isoprene emission capacities is also necessary to produce global

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1352-2310/$ – see front matter
http://dx.doi.org/10.1016/j.atmosenv.2013.11.055

emission inventories, and a number of different approaches have been employed by different investigators (Arneth et al., 2008; Guenther et al., 2006).

The output from these global models can be compared to top-down estimates derived from satellite observations of formaldehyde for both the continental (Palmer et al., 2007) and global scales (Shim et al., 2005). While estimates of global isoprene emissions from different investigators using different approaches produce a relatively narrow range (standard deviation less than 10% of the mean estimate) that agree with results from the top-down satellite data (Arneth et al., 2008), there remain a large number of uncertainties that could be constrained by more observational data. Considering the effect of changing the source of input variables like weather and land cover data and the comparison with satellite-derived estimates, a factor of two in uncertainty in global emission inventories is estimated (Guenther et al., 2012). The review of Arneth et al. (2008) identifies eight areas of uncertainty associated with global models of isoprene emission. Of these eight, four can be addressed by season-long isoprene flux measurements at a single site: emission algorithm, previous weather conditions, leaf-to-canopy scaling and leaf developmental stage.

The G93 leaf-level emission algorithm is the basis of many efforts to model ecosystem isoprene emissions, but there are questions about how some of the empirically-derived parameters vary (Arneth et al., 2008). For example, there have been reports that the response to light is more linear than predicted by G93 for tropical (Lerdau and Keller, 1997), temperate (Laffineur et al., 2013, 2011), and high-latitude (Potosnak et al., 2013) ecosystems. For the tropical and high-latitude ecosystems the discrepancies are from leaf-level observations; there are relatively few long-term ecosystem flux measurements that can test the performance of the algorithm. The response to drought stress in ecosystem models is also based on leaf-level drought studies (for example, Pegoraro et al., 2004). Many studies have found leaf-level isoprene emissions are less sensitive to drought than photosynthesis (for example, Brilli et al., 2007; Fang et al., 1996; Funk et al., 2005; Pegoraro et al., 2007, 2004) and Niinemets (2010) proposed a conceptual model where short-term drought stress has no effect on leaf-level isoprene emissions while a long-term stress decreases emissions.

The current study uses a season-long measurement record of ecosystem isoprene emission to validate a model at an oak-dominated forest in central Missouri. The dataset is used to explore the ability of the model to represent the magnitude of the observed fluxes, the shape of the diurnal cycle and the response to light. Because the measurements continued for most of the growing season, the influence of temperature and light regimes from the previous 10 days on current emissions can be assessed. Also, the occurrence of a drought during the measurement period provides another important test of the model.

2. Materials and methods

2.1. Site description, eddy-covariance and data analysis

The isoprene flux measurements were conducted at an existing site that is part of the AmeriFlux network (Baldocchi et al., 2001) for measuring ecosystem carbon dioxide (CO_2) exchange. The Missouri Ozark site is located in central Missouri (38°44.65′ N latitude, 92°12.00′ W longitude, 219 m elevation, http://ameriflux.ornl.gov/fullsiteinfo.php?sid=64, last retrieved Jul 15 2013) on the University of Missouri's Baskett Wildlife Research and Education Area. Further details of the site are described in Gu et al. (2006), but briefly, the site is an oak-hickory dominated broadleaf deciduous forest. The white (predominantly *Quercus alba* L.) and red (predominantly *Q. velutina* L.) oak groups account for 63% of the basal area and the non-emitters sugar maple (*Acer saccharum* Marsh.), hickory (*Carya* spp. Nutt.), ash (*Fraxinus* spp. L.), and juniper (*Juniperus* spp. L.) make up 33%. The basal area of the oaks varied from 70% to 150% of the mean across 5 transects from the tower base. Soils are relatively thin, which prevents the trees from accessing deep soil moisture during drought stress (Gu et al., 2006). During the period when isoprene fluxes were measured, leaf area index (LAI) was 3.7 m^2 m^{-2}, as measured by a LAI-2000 plant canopy analyzer (LI-COR, Lincoln, NE). The forest canopy is continuous within a 1-km radius of the site and the terrain is cut by small ravines with elevation changes of less than 50 m. Complete details of the eddy covariance technique and associated data analysis are described in the Supplementary Material file. The R language (R Foundation for Statistical Computing, Vienna, Austria, version 3.0.1) was used for data reduction and statistical analysis. The statistical significance of differences was determined with Student's *t*-tests.

2.2. Drought and plant water stress indicators

As substantial, recurring droughts are a significant phenomenon at the Missouri site (Bahari et al., 1985), multiple parameters of site and plant water status were available. The following were chosen for this study: 1) soil water content at 5 cm and 100 cm depths (Campbell Scientific CS616 water content reflectometers), predawn leaf water potential as an estimate of plant water stress (measured with a pressure chamber, Pallardy et al., 1991) and air vapor pressure deficit (VPD, derived from site meteorological data).

2.3. Modeling isoprene emissions

The measured isoprene fluxes were compared to the Model of Emissions of Gases and Aerosols from Nature, version 2.1 (MEGAN, Guenther et al., 2012). MEGAN calculates emissions as the product of a fixed canopy emission factor and an emission activity factor. The emission activity factor is driven by air temperature, photosynthetically active radiation (PAR), humidity and wind speed. The model uses a canopy radiation transfer scheme with five layers and a leaf temperature algorithm to predict isoprene emission rates for sunlit and shaded leaves at each level. Optionally, the model can use volumetric soil moisture content at two depths to account for water stress. This version of MEGAN optionally includes an algorithm that accounts for the influence of the preceding 24 and 240 h averaged values of leaf temperature and PAR. MEGAN was run with input meteorological variables at an hourly time step to predict isoprene fluxes, so the observed 30-min flux data were averaged to one hour to match. LAI was set to 3.7 m^2 m^{-2} to match the site.

The plant functional type was broadleaf deciduous temperate tree, and the vegetation fraction was set to 1. No parameters were changed from the values that MEGAN uses for estimating global isoprene emissions. The model was run with the canopy emission factor set to 10 mg m^{-2} h^{-1}, which is the MEGAN default for broadleaf deciduous temperate trees. The r^2 value for the fit of MEGAN using this canopy emission factor is reported. Next, a scale factor was calculated from a linear regression between the observations and the MEGAN results to infer a site-specific canopy emission factor, and the presented results include the application of this scale factor. As a comparison, ecosystem isoprene fluxes were also modeled using the big-leaf assumption (Geron et al., 1997). The big-leaf model employs the same framework of MEGAN, and the emission activity factor for the canopy is calculated using the leaf-