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Quantifying the contribution of environmental factors to isoprene flux interannual variability

Ahmed B. Tawfik [a,*], Reto Stöckli [b], Allen Goldstein [c,d], Shelley Pressley [e], Allison L. Steiner [a]

[a] Department of Atmospheric, Oceanic and Space Sciences, University of Michigan, Space Research Building, 2455 Hayward St, Ann Arbor, MI 48109-2143, USA
[b] Federal Office of Meteorology and Climatology MeteoSwiss Climate Services, Climate Analysis, Krähbühlstrasse, 588044 Zürich, Switzerland
[c] Department of Environmental Science, Policy and Management, University of California at Berkeley, 137 Mulford Hall, Berkeley, CA 94720-3114, USA
[d] Department of Civil and Environmental Engineering, University of California at Berkeley, 760 Davis Hall, Berkeley, CA 94720-1710, USA
[e] Department of Civil and Environmental Engineering, Washington State University, 405 Spokane St, Sloan 101, PO Box 642910, Pullman, WA 99164-2910, USA

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ABSTRACT

Terrestrial isoprene emissions directly respond to leaf temperature, photosynthetically active radiation (PAR), soil moisture, and plant characteristics such as leaf area index (LAI). Prior work has estimated isoprene interannual variability at 5–25%, however the relative contributions of individual environmental factors have not been delineated. A biogenic isoprene emissions model (MEGAN) is coupled to a regional climate model (RegCM4-CLM) to evaluate variations in monthly isoprene emissions. We use a novel approach to estimate the contribution of environmental factors to monthly averaged isoprene flux variability and analyze regional differences over the contiguous U.S. for summers spanning 1994–2008. Consistent with earlier studies, isoprene flux varies 8–18% interannually with the greatest variability occurring in July. Yearly changes in isoprene flux are poorly described by any single environmental factor, yet temperature and soil moisture together account for at least 80% of the total isoprene flux variations for all regions during the summer. Soil moisture plays the most significant role in controlling variability over the Northeast and Southeast, but only exceeds temperature in importance during August in the Northeast and July in the Southeast. PAR and LAI are nearly negligible contributors to summer interannual variability. Uncertainty in climate model soil moisture parameterizations can drive large variability in isoprene fluxes when including the isoprene soil moisture dependency factor, suggesting a need for further validation.

1. Introduction

Isoprene (C_5H_8) is an important ozone precursor in the presence of nitrogen oxides (NO_x) (Chameides et al., 1988) and its oxidation products can condense to produce secondary organic aerosols (Dentener et al., 2009). Both tropospheric ozone and atmospheric aerosols can lead to poor air quality and also influence the Earth's radiative budget either directly or indirectly (Andreae and Rosenfeld, 2008; Zhao et al., 2011). The primary source of isoprene to the atmosphere is emissions from terrestrial vegetation, with global estimates between 400–700 Tg yr^{-1} (Guenther et al., 2006; Arneth et al., 2008; Muller et al., 2008; Ashworth et al., 2010). Isoprene emissions are known to be controlled by several environmental factors, including temperature (Petron et al., 2001), light (Sharkey et al., 1996), soil moisture (Llusia et al., 2008), ambient carbon dioxide (CO_2) concentrations (Wilkinson et al., 2009), and phenology (Kuhn et al., 2004). As coupled climate-chemistry models move toward long-term simulations of tropospheric chemical environments (Fu et al., 2011), it is necessary to understand how individual environmental factors contribute to interannual isoprene flux variability.

Past studies have used observed isoprene concentrations and fluxes to estimate isoprene flux variability. In a hardwood forest site in Michigan, four years of canopy-level isoprene flux measurements showed low (~10%) inter-annual variability during the summer (Pressley et al., 2005). Although year-to-year variability at this site was strongly correlated to light and temperature, other unnamed environmental variables were implicated in controlling emissions variations. In Texas, two studies have investigated isoprene flux interannual variability (Gulden et al., 2007; Warneke et al., 2010). Gulden et al. (2007) concluded that modeled summer emissions yielded greater interannual variability when leaf area index (LAI) was allowed to respond to atmospheric forcing data

* Corresponding author. Tel.: +1 734 936 0511.
E-mail addresses: abtawfik@umich.edu (A.B. Tawfik), reto.stoeckli@meteoswiss.ch (R. Stöckli), ahg@berkeley.edu (A. Goldstein), spressley@wsu.edu (S. Pressley).

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(25%) as opposed to the typical LAI annual climatology (12%). In the second study, aircraft measurements of isoprene concentrations were used to infer isoprene emissions over northeastern Texas in 2000 and 2006 (Warneke et al., 2010) and found a factor of two difference in isoprene flux estimates between the two years. This difference was attributed to the unusually warm and dry conditions recorded in the summer of 2000, however the factor of two uncertainty in the inferred isoprene emissions is comparable to inter-annual variability. Comparing these inferred isoprene fluxes to several emissions inventories, Warneke et al. (2010) further demonstrated that models had difficulty capturing the observed interannual variation and was likely due to the lack of a direct soil moisture suppression of emissions during drought stress and/or lack of yearly varying LAI. However, neither of the two Texas studies account for direct emission suppression under decreasing soil moisture, which has been found to reduce global emissions by 20% (Muller et al., 2008).

At the regional scale, satellite-derived observations of formaldehyde column concentrations have been used to infer top-down isoprene emission fluxes and quantify isoprene flux interannual variability (Abbot et al., 2003; Palmer et al., 2006; Duncan et al., 2009). Abbot et al. (2003) used this technique with the Global Ozone Monitoring Experiment (GOME) satellite to estimate August interannual variability of 30% over the southeastern United States. They found that flux variations followed surface air temperature but interannual changes in temperature alone could not explain the variations in isoprene emissions. Palmer et al. (2006) also used GOME formaldehyde measurements to quantify interannual variability and estimated a range between 22–35% during the summer and suggested that 75% of variations are controlled by surface temperatures. In Palmer et al. (2006), the temperature-driven variation was estimated from the temperature dependency algorithm of an empirically-based isoprene emissions model (Guenther et al., 1995). A subsequent study focusing on the southeastern U.S. and utilizing higher resolution formaldehyde measurements (Ozone Monitoring Instrument; OMI) were in agreement with earlier estimates of variability (22% for the summer) and also implicated temperature as the primary driver (Duncan et al., 2009).

A global study using an interactive vegetation model supports the importance of land use in emissions calculations and estimates lower interannual variability (10%) for North America (Lathiere et al., 2006), yet we note that this study also does not account for emissions reductions due to soil water limitations (Guenther et al., 1995). Arneth et al. (2011) found that different isoprene emissions algorithms using the same climate forcing data estimated similar isoprene flux interannual variability. This suggests that climate variables (e.g. temperature, radiation, LAI, and soil moisture) play a strong role in controlling year-to-year emissions changes. Further, Arneth et al. (2011) found that interannual variability over the mid-latitudes was relatively small (5–10%) and attributed this to conflicting climate variable interactions. For example, warmer temperatures that increase emissions are well correlated with drier soils, which decrease emissions. This further emphasizes the need to quantify the role each control variable has on emissions variations.

Several of these studies (Pressley et al., 2005; Duncan et al., 2009; Warneke et al., 2010) cited are for specific locations where differences in observed isoprene flux variability may reflect regional differences. This highlights the need for a multi-region analysis of isoprene variability. As noted by Duncan et al. (2009), evaluating the influence of an individual climate variable on observed isoprene flux variability is difficult due to the strong correlations between climate variables. Although prior studies have provided estimates of the isoprene flux variability, there is little attribution of each environmental factor to flux variability that accounts for the direct effect of soil water limitations on emissions. Studies that include the soil moisture dependency can reduce global emissions up to 7–20% (Guenther et al., 2006; Muller et al., 2008) and can improve regional agreement with observations (Muller et al., 2008). Additionally, most studies operate on global domains and use land models forced with half-hourly or longer atmospheric data, resulting in coarse temporal and/or spatial resolution. Due to the heterogeneous nature of isoprene source strength and the sensitivity to temporal resolution of climate data (Ashworth et al., 2010), using a coupled, high-resolution regional model is likely to improve understanding of the influence of environmental factors on isoprene flux variability. The primary objectives of this study are to quantify the relative contributions of temperature, light, LAI, and soil moisture on isoprene emissions variability and to assess regional differences in the environmental variables controlling emissions over the contiguous U.S. A secondary goal is to introduce a simple methodology for calculating percent contributions of the environmental dependency factors that could be applied to other environmental control variables not considered in this study.

2. Methods

A biogenic emissions model (the Model of Emissions of Gases and Aerosols from Nature; MEGAN) (Guenther et al., 2006), described in Section 2.1, is coupled to the International Centre for Theoretical Physics (ICTP) Regional Climate Model version 4 (RegCM4; (Giorgi et al., in press)) to examine the relative contributions of leaf temperature, soil moisture, photosynthetically active radiation (PAR), and LAI to biogenic isoprene emissions. RegCM4 is a compressible, hydrostatic, primitive-equation model with a land surface described by the Community Land Model version 3.5 (Oleson et al., 2008), which determines the canopy-scale environment variables for input into MEGAN (Section 2.2). Based on RegCM4-CLM-MEGAN model output, the contribution of individual environmental factors is calculated as described in Section 2.3.

2.1. Biogenic isoprene emissions model: MEGAN

MEGAN is a biogenic emissions model (Guenther et al., 2006) that parameterizes observed relationships to estimate emissions. The canopy environment version of MEGAN determines isoprene emissions for each model grid cell as:

$$E = \varepsilon \rho C_{CE} \gamma_{PT} \gamma_{SM} \gamma_{age} \mathrm{LAI} \quad (1)$$

$$\gamma_{PT} = \gamma_T(\gamma_{Psun} + \gamma_{Pshade}) \quad (2)$$

where E is the isoprene emission flux ($\mu g\, h^{-1}\, m^{-2}$), ε is a standard emission factor taken at standard conditions described in Guenther et al. (2006) ($\mu g\, h^{-1}\, m^{-2}$), ρ is the in-canopy loss or production factor (=0.96), C_{ce} is an empirical adjustment factor for the canopy environment (=0.4), and γ_T, γ_P, γ_{SM}, and γ_{age} describe the influence of leaf temperature, PAR, soil moisture, and leaf age on isoprene emissions, respectively. The canopy description is based on that of the RegCM4 land model, the CLM version 3.5. CLM contains a single layer canopy model that is divided into sunlit and shaded fractions, which allows the calculation of γ_P and emissions based on the fraction of sunlit and shaded leaves (Eq. (2)). A high-resolution 30″ emission factor map, ε, is used (http://cdp.ucar.edu) and bi-linearly interpolated to the model gridcell-level and is not linked to the CLM land cover type. The effects of past temperature and light conditions on time scales of 24 hours and 10 days are included in the current implementation.