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Overlooking the canopy: The importance of canopy structure in scaling isoprenoid emissions from the leaf to the landscape

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ABSTRACT

Isoprene and monoterpenes are highly reactive organic compounds, emitted by most plant species, which play an important role in air chemistry and air pollution. Different leaf-scale isoprenoid emission models are available. These models are scaled to the canopy through coupling them to terrestrial biogeochemical models and thus used to generate regional emissions inventories. Although the leaf scale models have been shown to perform similarly, large unexplained differences exist in regional emissions inventories. This may be explained in part by the complete lack of inter-comparisons of emission model estimates when scaled from the leaf to the canopy.

In this paper we address this problem by coupling four different isoprene emission models (Guenther et al. model, Niinemets et al. model, BIM2 and the Martin et al. model) to two terrestrial biogeochemical model platforms (MoBiLE, GOTILWA+) that describe canopy structure differently. Simulations of isoprene emissions for the Puechabon Mediterranean holm oak stand are analysed, with both canopy photosynthesis models constrained using FLUXNET measurements.

The results demonstrate that even with constrained canopy level photosynthesis, large model platform dependent within canopy differences can exist in both modelled photosynthesis and emissions. This results in large differences in modelled isoprenoid emissions, due to the relatively higher sensitivity of emissions to canopy microclimate, in particular temperature. This is the first time emission results from two biogeochemical platforms have been compared, and demonstrates that different canopy descriptions can lead to larger differences in modelled emissions than that attributable to the difference between the emission models themselves. This is an important aspect that has not been acknowledged by the emission modelling community.

1. Introduction

Biogenic volatile organic compounds (BVOCs), which are emitted by most plants, are a highly important component of plant–atmosphere interactions. BVOCs play an important role in plant–insect communication (Laothawornkitkul et al., 2008; Miller et al., 2005) and in regional air chemistry (e.g., Fuentes et al., 2000; Kanakidou et al., 2005; Liakakou et al., 2007; Papiez et al., 2009). Indirectly, they also contribute to climate change by modifying the lifetime of methane (Poisson et al., 2000; Collins et al., 2002). Due to their possible feedbacks in plant physiology and high importance for air chemistry (see Sharkey et al., 2008 for a review) simulating BVOC emission has been a major objective of modellers throughout the last 20 years. The developed approaches focus on the leaf scale emissions, due to the relative ease of obtaining leaf scale measurements. However, these leaf scale emissions must be scaled to the canopy for the estimation of site or regional emissions. A mechanistic representation of BVOC emission therefore requires the consideration of possible factors that affect emissions not only in time but also within the canopy.

Whilst the problem of estimating terrestrial BVOC emissions is of great concern both at the local and regional scale, the few methods available for estimating emissions have all been developed at the leaf scale (Guenther et al., 1993; Niinemets et al., 1999; Martin et al., 2000; Zimmer et al., 2000; Bäck et al., 2005). Making reliable estimates of local or regional emissions necessitates scaling the short-term leaf level emission models to the forest canopy, and thus to the landscape. The most common scaling approach is of coupling the emissions model to a process based ecophysiological

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model (which describes the forest structure and canopy micrometeorological conditions) (e.g., Lamb et al., 1993; Lenz et al., 1997; Baldocchi et al., 1999). Only after such scaling can the emission models be used as input for mechanistic air chemistry models for further extrapolations (e.g., Collins et al., 2002; Kulmala et al., 2004; Tunved et al., 2006). However, canopy scale data is very scarce (see Pacifico et al., 2009), and limited to a few sites with specific conditions. Only relatively recently have methodologies such as eddy-covariance techniques been developed that allow quantitative measurements of canopy BVOC emission (Ciccioli et al., 2003; Spirig et al., 2005). Thus the scaling of emissions to the canopy has as yet been subject to limited testing, with all studies known to the authors focused exclusively on the testing/comparing of one or more emissions model when scaled to the canopy level using a single ecophysiological model platform (thus omitting potential inter-platform differences) (e.g., Arneth et al., 2007; Keenan et al., 2009b; Grote et al., 2010). In the vast majority of studies a particular model combination is then used directly to estimate regional or global emissions (with no discussion of inter-model variability), with results varying widely between studies (Arneth et al., 2008).

The non-linearity of the relationships between photosynthesis on leaf nitrogen and absorbed light, and changes in leaf microenvironment with canopy depth, complicate the task of scaling leaf physiology to the canopy. It has long been acknowledged that the treatment of the canopy as one "big leaf" with mean characteristics and submitted to an average radiation flux leads to significant errors in estimating canopy level carbon and water fluxes (Sinclair et al., 1976; Spitters et al., 1986). Canopy structure can theoretically be accounted for by either using a simple canopy stratification model, or a modified big-leaf approach with distinction of sunlit and shaded fractions (Raupach and Finnigan, 1988). These methods differ in their treatment of the heterogeneity of the microclimate within canopy. An effective multilayer approach has been proposed which divides the canopy into multiple layers for which environmental and physiological variables are calculated and assimilation determined (e.g., Wang and Jarvis, 1990; Collatz et al., 1991; Lamb et al., 1993). This approach allows the integration of within-canopy profiles, and is commonly applied in stand scale models, but is computationally relatively expensive, thus restricting its application over large regions. Even at the stand scale, its use is complicated by the lack of detailed within canopy measurements for parameterisation. On the other hand, sunlit and shaded leaves can be treated separately also in one or two layers only (e.g., Sinclair et al., 1976; Sellers et al., 1992; Amthor, 1994; Leuning et al., 1995). The averaging of the radiation absorption caused by the reduction of the number of layers does not result in a loss of precision, because the response of the photosynthesis of shaded leaves to absorbed solar radiation is quasi-linear whilst sunlit leaves assimilate CO_2 at a constant saturated rate. In this manner, even one single layer can be used (with sun/shade division) (De Pury and Farquhar, 1997; Wang and Leuning, 1998) assuming that the vertical profiles of leaf photosynthetic capacity and absorbed radiation follow theoretical distributions that can be integrated analytically when they are multiplied by the vertical distribution of the sunlit/shaded area fraction.

These two kinds of canopy models have been expressively designed and tested to effectively model photosynthesis and transpiration under various conditions (e.g., Reynolds et al., 1992; Friend, 2001). However, uncertainties associated with the choice of canopy microclimate models have been highlighted as potentially having a large impact on estimated emissions (Guenther et al., 2006; Grote, 2007). Various model analyses (e.g., Larsen and Kershaw, 1996; Huber et al., 1999; Grote, 2007) have confirmed that the relative lack of knowledge of the spatial distribution of foliage increases the uncertainty in emission simulations (this conclusion has been questioned by Geron et al., 1997). It therefore seems likely that the description of the canopy model (and the resulting distribution of temperature and light within the canopy) will have large ramifications for the estimated emissions, in particular when taking into account the different emission model sensitivities to temperature and light (Arneth et al., 2007; Keenan et al., 2009b). This is of increasing importance when considering the potential impact of projected future climatic change and species-specific responses (e.g., Peñuelas and Llusia, 2001). Studies show that the within canopy distributions of environmental conditions as well as foliage properties are highly important for scaling emission from the leaf to the canopy (Baldocchi et al., 1999; Harley et al., 2004; Grote, 2007). Despite relatively extensive model testing (e.g., Arneth et al., 2007; Keenan et al., 2009b), no study has assessed the effect that the chosen canopy model has on estimated emissions from different models. Differences in light and temperature distribution within a forest model canopy may in part explain the large reported differences (Arneth et al., 2008) in regional emissions inventory estimates.

Here, we couple four different isoprene emission models to two different ecosystem model platforms (MoBiLE and GOTILWA+), driven by the same climatic data at the same site, and constrained by continuous eddy-covariance carbon and water flux measurements. Each model platform applies one of the two most commonly used approaches to scale leaf emissions to the canopy (stratified vs. big leaf canopy descriptions), which we parameterise separately using canopy measurements from the same forest. We focus on isoprene because it is the most commonly modelled BVOC. Although *Quercus ilex* emits only small amounts of isoprene relative to monoterpenes, both emission types follow the same light and temperature dependent fashion and are modelled in the same way. Thus, it is assumed to be a suitable species to investigate the sensitivity of emissions from non-specific storages in general. Four isoprene emission models are coupled to each model platform, allowing us to test the effect the choice of canopy description has on estimated isoprene emissions.

2. Materials and methods

2.1. Site description and data availability

Data and simulations refer to a study site located 35 km NW of Montpellier (southern France) in the Puechabon State Forest (3°35′45″E, 43°44′29″N, elevation 270 m). Vegetation is largely dominated by a dense over-storey of holm oak (*Q. ilex*) trees (upper canopy height 6.0 m, rooting depth down to 4.5 m). The climate is typical Mediterranean with cool and wet winters and warm and dry summers. The mean annual temperature is 13.5 °C and mean annual precipitation is 872 mm. Soil texture is homogeneous down to 0.5 m depth and can be denoted as silty clay loam (referring to the textural triangle, United States Department of Agriculture), with a limestone rock base. For more details on the site see http://www.cefe.cnrs.fr/fe/puechabon/.

Due to the Mediterranean-type climate and the low water holding capacity (210 mm), the water content in summer falls regularly below the value at which water stress limitations to photosynthesis are expected (Rambal et al., 2003; Keenan et al., 2009a). The timing and extent of soil water availability vary from year to year. Water content decreases to values close to the wilting point in almost every year. The selected example year, 2006, was slightly warmer and dryer than the long-term average (total precipitation 773 mm, annual average temperature of 14.1 °C, see also Allard et al., 2008). Considering that the long-term average is derived from the past 30 years, and that the temperature is expected to increase by up to 5.1 °C by 2055 (Bravo et al., 2008) with co-occurring decreases in precipitation, 2006 is assumed to well represent current conditions.